

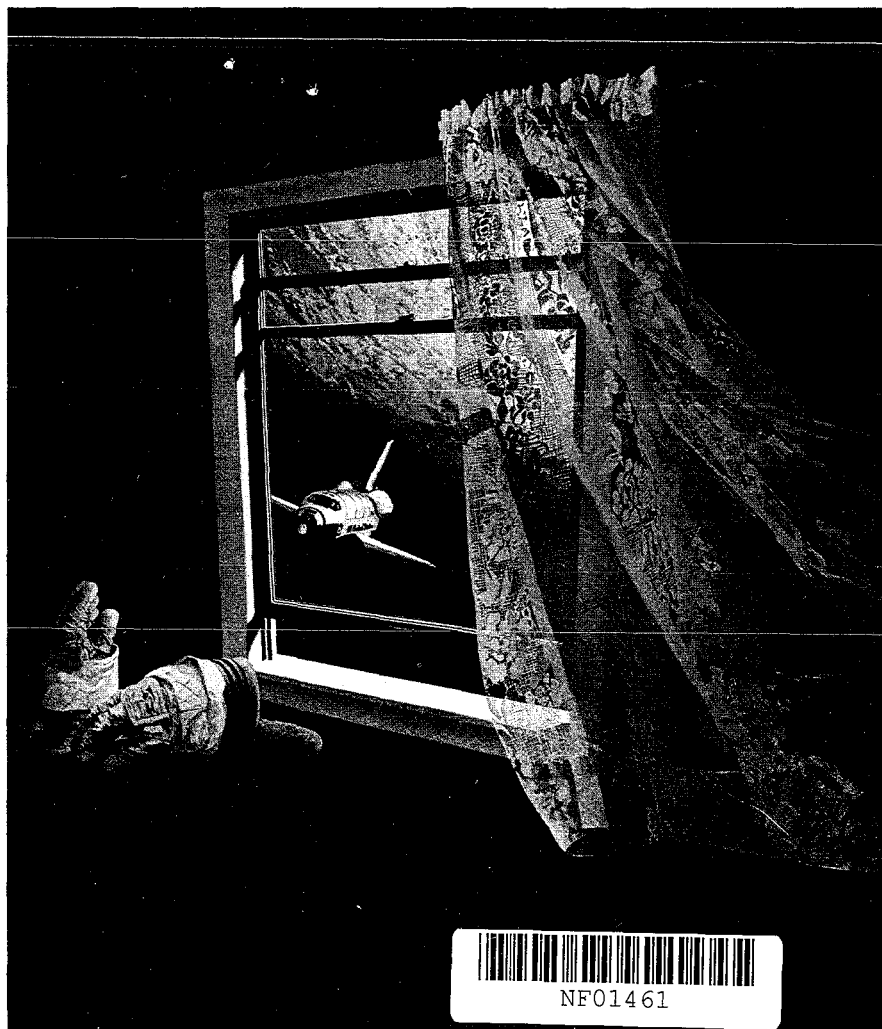
BOEING

Space Station Needs, Attributes, and Architectural Options Study

Volume 6
Final Report
Final Briefing
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RESEARCH INSTITUTE OF MICHIGAN

 **INTERMETRICS**

Microgravity
Research
Associates, Inc.





Econ
INCORPORATED

Space Station Needs, Attributes, and Architectural Options Study

Contract NASW 3680

Final Executive Review

April 5, 1983

**Space Systems Division
Boeing Aerospace Company
Seattle, Washington**

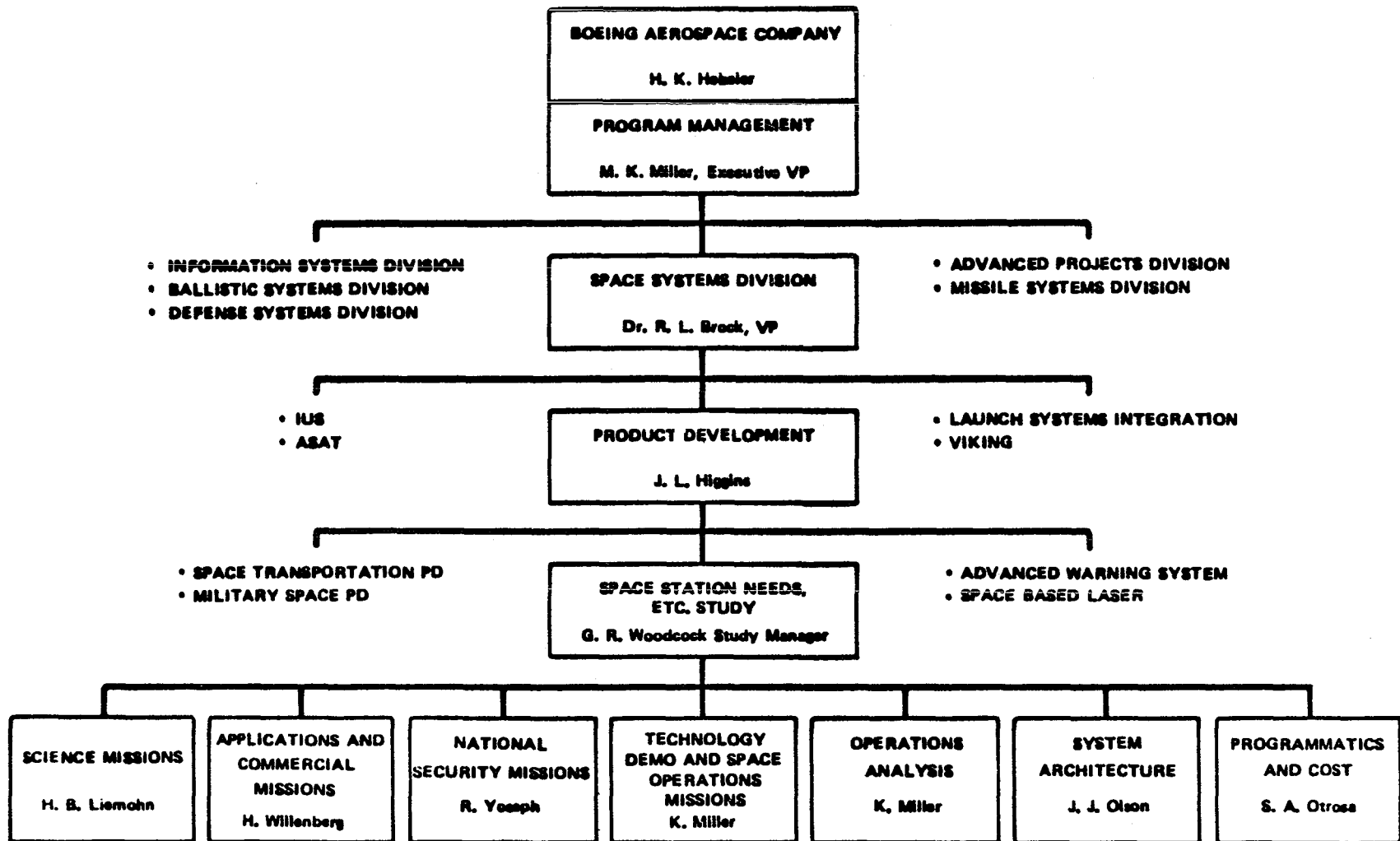
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TEAM ORGANIZATION

The Space Station Needs, Attributes, and Architectural Options Study was conducted by the Boeing Aerospace Company Space Systems Division. The study was managed by G.R. Woodcock with principal task managers as identified on the facing page. The NASA Contracting Officer's Representative was Brian Pritchard.

Team Organization

SS-571



SUBCONTRACTS

We drew on a broad base of small subcontracts to obtain the best available expertise in subjects of primary importance. Most of our subcontract activity concentrated on mission analysis. In addition, we subcontracted to the two principal suppliers of environmental control and life support equipment in order to obtain a broad base of expertise as to preferred ECLS technology.

Because of the potential high cost of software we subcontracted with Intermetrics for consultation on software development and management procedures.

Econ, Inc. collaborated in the development of economic benefits and pricing policies.

Recognizing the importance of habitability and social/psychological factors to optimizing human performance in space, we subcontracted with National Behavioral systems to provide consultation on crew accommodations and their influences on architectural approaches.

Subcontracts

SS-573

	WHO	WHAT	WHY
MISSIONS	<p>ARTHUR D. LITTLE</p> <p>BATTELLE</p> <p>ENVIRONMENTAL RESEARCH INSTITUTE OF MICHIGAN (ERIM)</p> <p>MICROGRAVITY RESEARCH ASSOCIATES</p> <p>RCA</p> <p>SAI</p>	<p>MATERIALS PROCESSING IN SPACE</p> <p>MATERIALS PROCESSING IN SPACE</p> <p>EARTH OBSERVATION MISSIONS</p> <p>MATERIALS PROCESSING IN SPACE</p> <p>COMMUNICATIONS SPACECRAFT</p> <p>SPACE SCIENCE</p>	<ul style="list-style-type: none"> • EXPERIENCE WITH MANY INDUSTRIAL CLIENTS • INSTITUTIONAL PERSPECTIVE • EXPERTISE ON ONE SPECIFIC BIOLOGICAL • BROAD EXPERTISE IN CIVIL AND MILITARY APPLICATIONS • USER ORIENTATION • COMMERCIAL MARKET POTENTIAL IS LARGE • ACQUIRE IN-DEPTH UNDERSTANDING OF NEEDS AND BENEFITS • TYPICAL ENTREPRENEURIAL INVESTMENT COMPANY • USER ORIENTATION – ESSENTIAL FOR THIS APPLICATION • ACQUIRE IN-DEPTH UNDERSTANDING OF NEEDS AND BENEFITS • USER ORIENTATION – SPACE SCIENCE EXPERTISE
SUBSYSTEMS	HAMILTON STANDARD; LIFE SYSTEMS INTERMETRICS	ENVIRONMENTAL CONTROL AND LIFE SUPPORT EQUIP SOFTWARE	<ul style="list-style-type: none"> • EXPERTISE IN EQUIPMENT CHARACTERISTICS, TECHNICAL RISKS AND COSTS • EXPERIENCE IN NASA S/W INTEGRATION
BENEFITS	ECON	PRICING POLICIES AND ECONOMIC BENEFITS	<ul style="list-style-type: none"> • EXPERTISE ON NASA COSTS, ECONOMICS AND POLICIES • EXPERTISE ON ECONOMIC METHODOLOGY
ATTRIBUTES	NATIONAL BEHAVIORAL SYSTEMS	CREW ACCOMMODATIONS AND ARCHITECTURAL INFLUENCES	<ul style="list-style-type: none"> • EXPERTISE ON SOCIAL/PSYCHOLOGICAL FACTORS IN HUMAN PERFORMANCE IN STRESSFUL ENVIRONMENTS

AGENDA OF ISSUES

The final briefing follows the agenda shown on the facing page. The briefing addresses these prominent issues.

Agenda of Issues

- **Identification and validation of missions**
- **Benefits of manned presence in space**
- **Needed attributes and overall architectures**
- **Requirements imposed on space station**
- **Selection of orbits**
- **Space station architectural options**
- **Technology selection**
- **Program planning**
 - **Costs and benefits**
 - **Risk and cost avoidance**

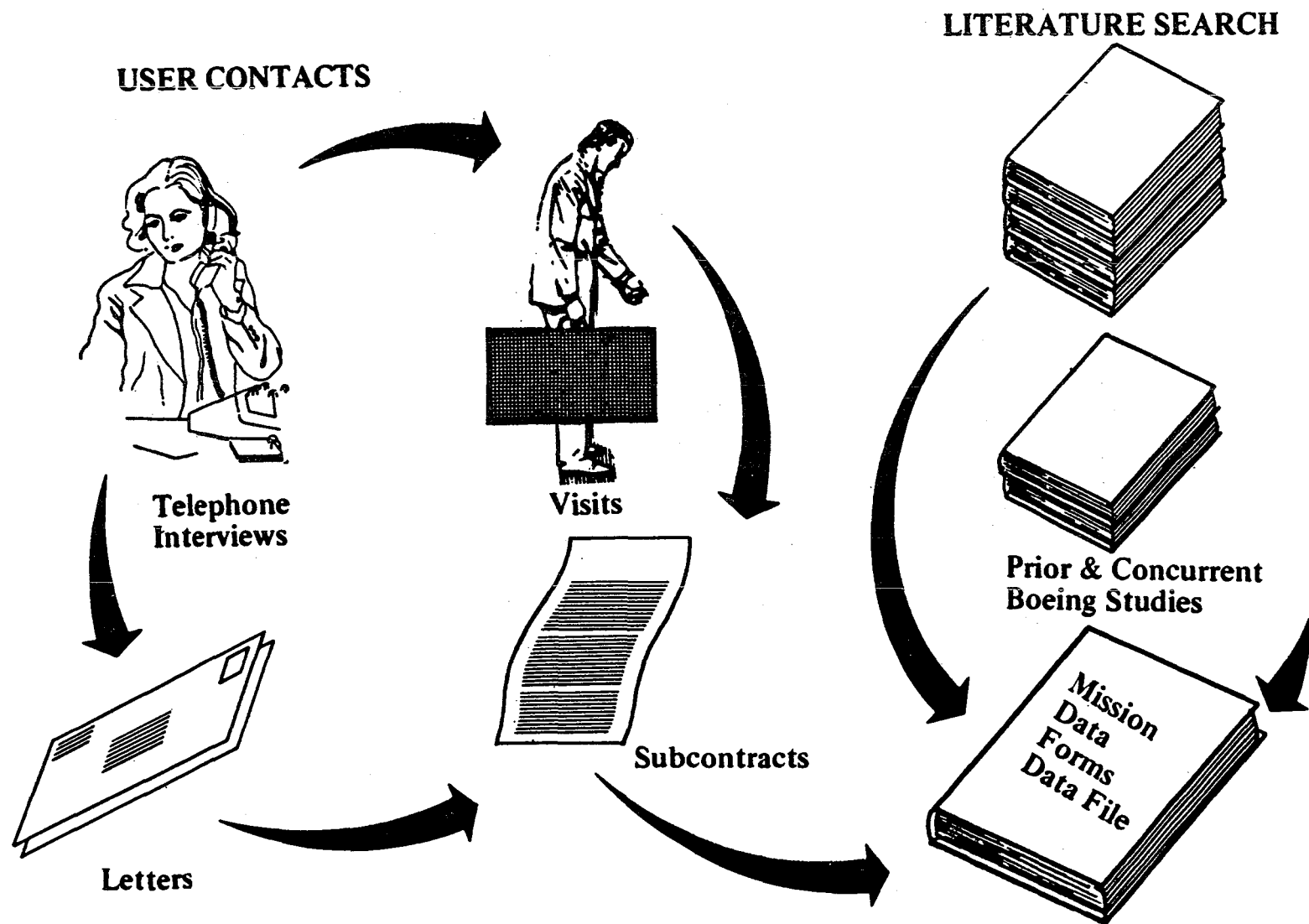
DEVELOPING MISSION NEEDS DATA

Mission needs data were developed by a combination of user contacts and literature search. The bulk of the effort went into user contacts inasmuch as most of the relevant literature was already on hand and understood.

Our most effective means of obtaining broadly-scoped input was telephone interviews. We found that our mission investigators could contact a wide range of users and get the essential information from each in a relatively few minutes. Letters, however, were often unanswered. In cases of high interest we undertook visits to specific potential users to gather data in greater depth. In certain areas, principally communications, spacecraft, and microgravity processing we considered subcontracts essential to developing a thorough understanding of mission utility and benefits.

All user data input was compiled on mission data forms and recorded in a computer data file. This provided the source record from which the space station missions were developed.

Developing Mission Needs Data



DEVELOPING THE SPACE STATION MISSION MANIFEST

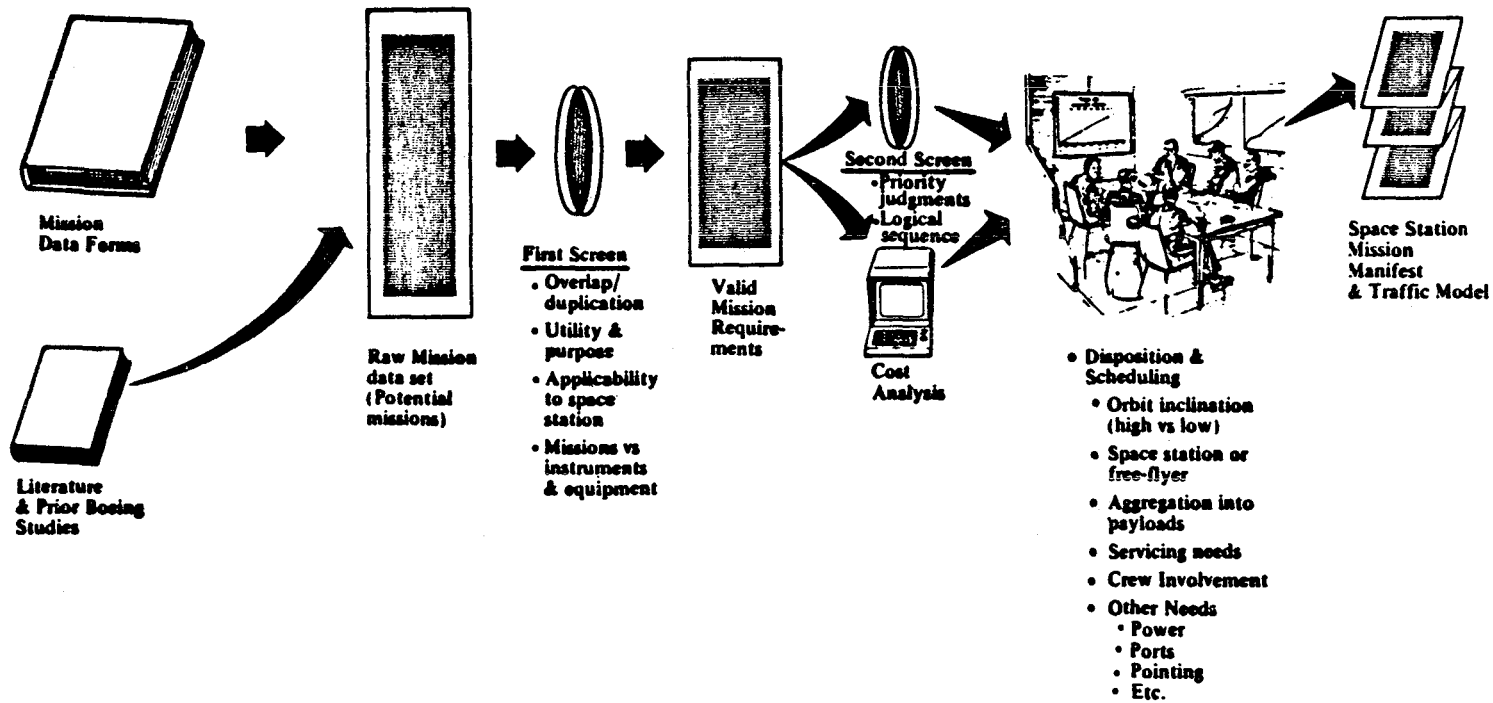
The mission data forms and literature data provided a raw mission data set of potential missions. This raw mission data set had several problems. Firstly, there was significant overlap and duplication among different mission categories. Secondly, although scientific mission inputs were usually clear on utility and purpose, this was not true in some other areas. Judgements were made as to whether each mission had sufficient utility and purpose to be retained.

Thirdly, some of the user mission inputs had little relationship to space station. Finally, many of the inputs were missions stated in terms of objectives or science results instead of instrument or equipment requirements. Consequently, we found it necessary in a number of cases to matrix missions versus instruments and equipment to avoid duplication of instrument needs.

The result of this initial screening provided a set of valid mission requirements. At this point we applied additional screening criteria, including judgements as to relative priority and logical sequencing, combined with cost analysis of mission equipment, to feed a process of disposition and scheduling. This process considered orbital inclination, placement of the mission on a station versus a free flyer, aggregation of smaller units into meaningful space station payloads, identification of servicing and support needs, crew involvement, and scheduling consistent with reasonable budgetary expectations.

The final result was a space station mission manifest and traffic model. This mission manifest featured aggregation of missions into 46 logical payloads, such as an earth observation pallet including eight instruments, and a life sciences research facility responsive to dozens of individual life sciences missions.

Developing the Space Station Mission Manifest



SCIENCE MISSION DISPOSITION

The facing page illustrates the manifest results for the science missions. It shows the orbit inclination, when the mission is active, crew involvement for either conducting the mission itself or for servicing the mission or equipment, placement and finally servicing means.

Those missions described as carry-ons are missions that did not require specific manifesting on space transportation, but did demand space station services.

Science Mission Disposition

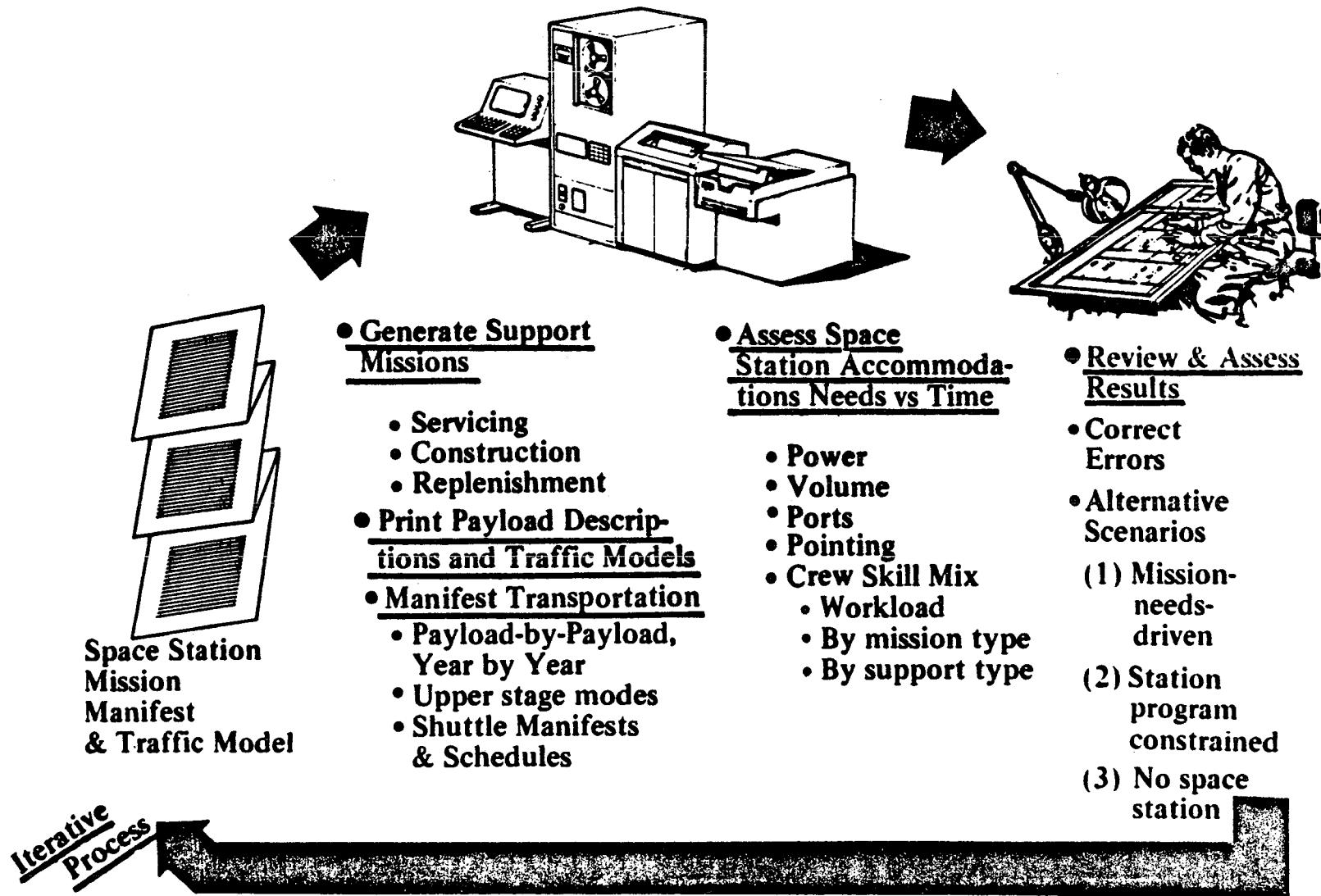
MISSION	ORBIT (DEG.)	TIMING				CREW INVOLVEMENT		PLACEMENT	SERVICING MEANS
		90	95	00	05	MISSION OPS	SERVICING		
EARTH OBSERV PALLET	96		_____			X	X	ON SPACE STA	IVA/EVA
SYNTH APERTURE RADAR	96		_____			X	X	ON SPACE STA	IVA/EVA
LIDAR	96			_____		X	X	ON SPACE STA	IVA/EVA
UPPER ATM	96			_____		X	X	ON SPACE STA	IVA/EVA
SCI SUBSAT	96	_____	_____				X	FREE FLYER	EVA
SPACE PHYS	96		_____		_____		X	ON SPACE STA	IVA/EVA
VLBI/COSMIC RAY	96	_____	_____	_____			X	ON SPACE STA	IVA/EVA
RADIATION BIOL	96			_____	_____	X	X	CARRY-ON	IVA
HUMAN LIFE SCI	29	_____	_____			X	X	CARRY-ON	IVA
SM MAMMALS	29	_____	_____			X	X	CARRY-ON	IVA
PLANT DEV	29	_____	_____			X	X	CARRY-ON	IVA
LIFE SCI RF	29		_____	_____		X	X	DEDIC MODULE	IVA
CELSS MOD	29			_____		X	X	DEDIC MODULE	IVA
ASTROPHYS OBS	29	_____	_____	_____			X	FREE-FLYERS	EVA/TMS
ASTROPHYS PLAT	29		_____		_____		X	FF PLATFORM	EVA/TMS
ASTRO/SOLAR CLUS	29	_____		_____		X	X	ON SPACE STA	IVA/EVA
LARGE RADIOTEL	29			_____			X	FREE-FLYERS	EVA CONSTRUCT EVA/TMS SERV

DETERMINING MANIFESTING AND ACCOMMODATIONS NEEDS

Determining the manifesting and accommodations needs is a computation intensive process. We used an automated procedure to speed up this effort. This procedure carries out the functions annotated on the facing page, to assess both transportation needs and space station accommodations needs.

The results of these computations were reviewed and assessed in order to correct errors and to generate alternative scenarios. We created three scenarios for this study. First, was a mission-needs-driven scenario; secondly, a program-constrained scenario in which missions were deferred to slow the rate of growth of space station needs; and thirdly, a scenario with no space station but with automated platforms, to provide evaluation of the benefits of manned presence.

Determining Manifesting & Accommodations Needs



SCIENCE AND APPLICATIONS MISSION NEEDS

Science and applications missions can be served by high inclination and low inclination space stations. The high inclination space station conducts earth observation missions and those plasma physics missions that need to be exposed to the auroral zones. The low inclination missions included materials processing, life sciences and astrophysics and solar observations.

The benefits of crew presence are mainly in instrument and equipment servicing, and in direct involvement in the missions themselves. The principal categories of crew activities are noted on the facing page. A major benefit of the space station is in manned servicing of instruments. This enables the accumulation of science instrument assets in space over long periods of time rather than expending available science funds on instrument replacement, as is true today.

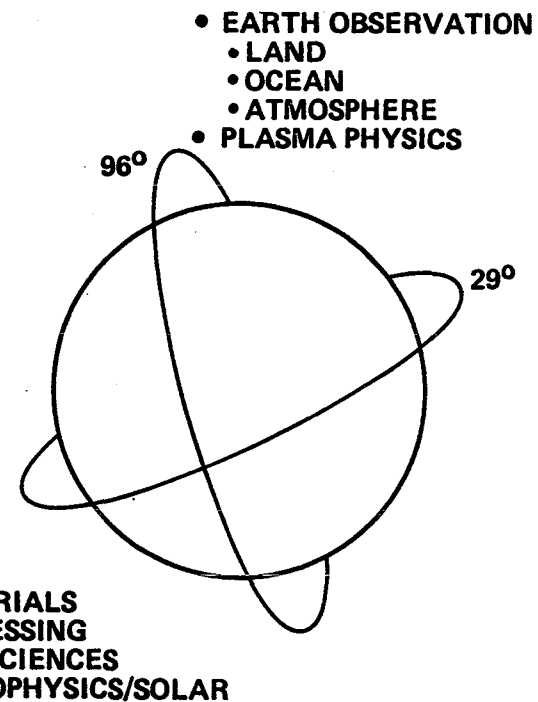
We also found that most life sciences, and some materials, astro-and solar physics missions were impractical without crew presence. Crew presence contributes to earth observation missions through selecting targets of opportunity and coordinating instrument operations.

Science & Applications Mission Needs

- **Benefits of crew presence:**
 - **Instrument and equipment servicing**
(Predominant for Earth observation, Plasma Physics, and Astrophysics)
 - **Involvement in mission**
(Predominant in Materials Processing, Life Sciences, and Solar Physics)
 - Carry out experiments/act as subjects
 - Identify transient events and coordinate instruments

- **Servicing enables accumulation of instrument assets rather than replacement.**

- **Most Life Sciences, some materials, some astro/solar physics missions impractical without crew presence.**



COMMERCIAL MISSION NEEDS

Materials processing dominates the commercial mission needs. We found crew involvement to be essential for research and development as well as for production servicing operations. The role of manned presence is key in the development phase to enable rapid experimental progress. The materials processing missions offer high economic value and benefit.

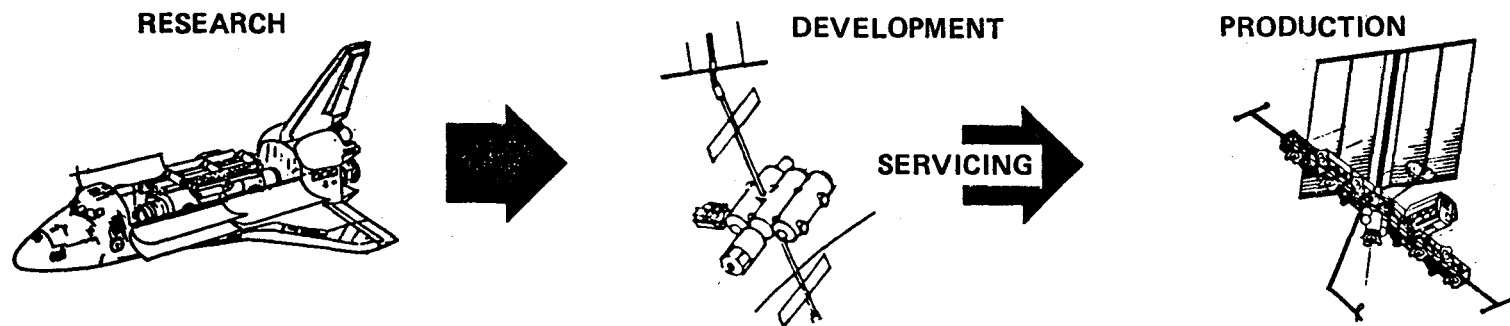
Semi-conductor crystal growth needs very high power in the production phase. Accordingly, it was deemed appropriate to allocate this mission to a separate free-flyer platform to avoid burdening the space station power system with this demand.

These missions need frequent shuttle flights and were the principal reason for traffic growth in the traffic model.

The space station enables some of these missions and enhances all of them.

Commercial Mission Needs

- MATERIALS PROCESSING PREDOMINATES
 - CREW INVOLVEMENT FOR DEVELOPMENT & PRODUCTION SERVICING AND PRODUCTION OPERATIONS
 - HIGH POWER, ESPECIALLY FOR PRODUCTION
 - FREQUENT SHUTTLE FLIGHTS
- SPACE STATION ENABLES SOME OF THESE MISSIONS, ENHANCES ALL.
- HIGH ECONOMIC VALUE & BENEFITS



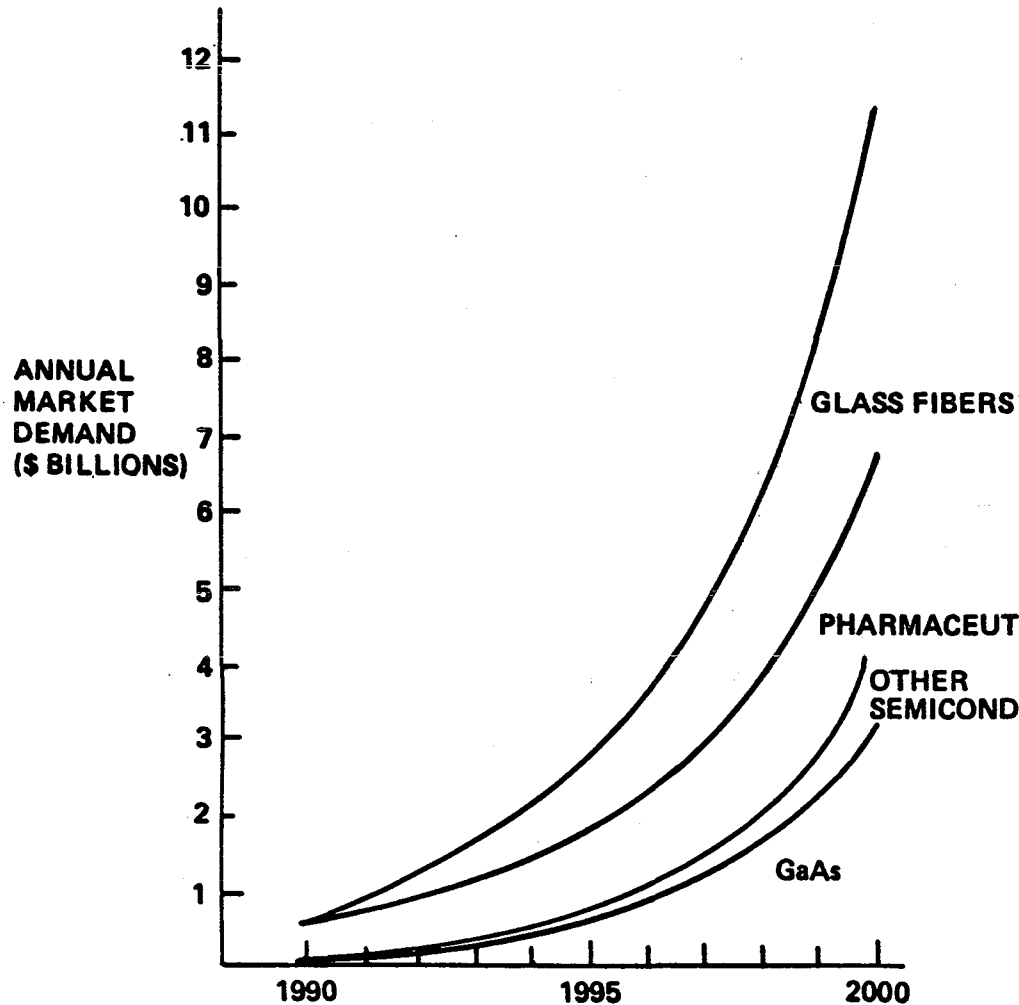
MARKET PROJECTIONS FOR MATERIALS PROCESSED IN SPACE

Hundreds of different materials processing experiments have been proposed. Many could undoubtedly lead eventually to commercial products. However, at the present state-of-the-art we were able to identify only three that have (1) definable market demands, (2) known processes that offer significant advantages over earth based processing and (3) product values high enough to absorb the high cost of space transportation. These were special semi-conductors, pharmaceuticals, and optical glass fibers. The market projections for these three areas are shown on the facing page and reach a cumulative market potential on the order of ten billion per year by the year 2000.

Whereas the market potential for each of these projected products is speculative and subject to certain risks it is indicative of the potential high economic value of materials processing in space. While one or more of these products may fall by the wayside it is likely that others will fall in place, especially if a space station is available with a materials processing laboratory to permit intensive micro-gravity materials research.

Market Projections for Materials Processed in Space

SS-670



GaAs DEMAND BEST-DEFINED

- GOVERNMENT/MILITARY
- DATA PROCESSING

OTHER SEMICONDUCTORS

- HgCdTe FOR IR DETECTORS
- IN P FOR COMPUTERS

PHARMACEUTICAL DEMAND LESS DEFINED

- LIVING CELLS BY ELECTROPHORESIS
- PROTEINS AND ENZYMES

OPTICAL GLASS FIBERS DEMAND UNCERTAIN

- COMMUNICATIONS
- COMPUTERS
- INTERFERENCE-FREE PROCESSORS

NEED TO ASSESS PURITY IN SPACE
AND COMPARE TO EARTH-BASED PROCESSES.

COMMUNICATIONS SATELLITES

To assess the benefit of a space station for servicing communication satellites, we felt it was essential to go to a satellite manufacturer for evaluation. Accordingly, we subcontracted with RCA Astro-electronics to investigate uses of a space station for communication satellites. RCA identified two applications.

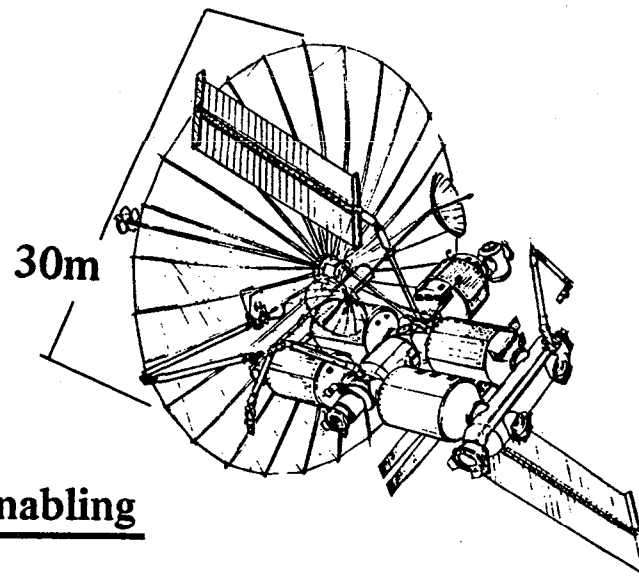
1. Reconfigurable direct broadcast satellite spares. The present concepts for direct broadcast TV satellites use one satellite to cover each U.S. time zone. Each of four active satellites will have a beam shape appropriate to its particular time zone. Because of the risk of an unplanned outage, hot spares must be available in orbit. One spare is required for each pair of time zones since it is possible to include two antenna feeds to create two beam shapes for each spare. The hot spares in geosynchronous orbit are using up their propellant and lifetime while waiting to be used in the event of an outage. Alternatively, a single hot spare could be held at a space station. Upon need for replacement, the proper feed horn would be installed and the satellite launched to the destination orbit. The satellite would include integral propulsion for quick response launch.
2. Assembly and test of large aperture antenna platforms. RCA identified potential needs for future communications satellites with antennas up to thirty meters in diameter as depicted in the lower right of the facing page. The space station provides the necessary crew participation in the construction process. The alternative is STS revisits to satisfy the construction time requirement. This alternative is risky because large aperture antenna systems have very short orbit lifetimes unless attached to a space station. Consequently, although we considered space shuttle revisits for construction, we believe the space station is enabling for large antenna construction in low Earth orbit.

Communications Satellites

Two applications identified by RCA

- (1) Reconfigurable direct broadcast satellite spares-space station provides: storage, installation of correct feedhorn, quick-response launch.
- (2) Assembly and test of large-aperture platforms space station provides crew involvement in construction—

Alternative is STS revisits for construction time.



Space station is essentially enabling for large antenna missions.

TECHNOLOGY DEVELOPMENT MISSIONS

Our original set of technology development missions totaled 76. The principal mission categories included space structures, large optics, flight controls, fluids, robotics, and energy technology. The number was cut to 33 by screening for duplication and overlap and applying budgetary considerations.

The 33 missions divided into three categories roughly equal in number. The first was environmental control and life support technology development missions, allocated to the space station technology and development program and not manifested for space transportation and space station operations. The other two categories were those that could be done without a space station (at greater cost) and those that require a space station. Of the applicable technology development missions identified, about 50% require a space station.

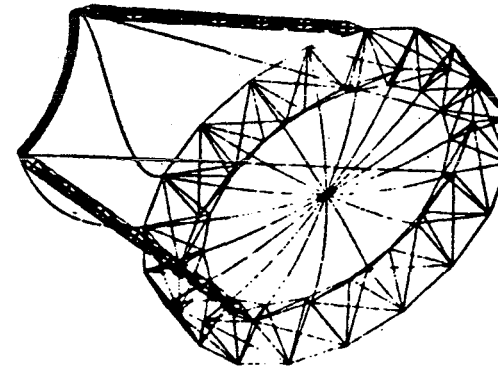
The space station is enabling for these missions because they require extensive crew involvement, and because some of them have very short orbit lifetimes unless attached to a space station.

In comparing the transportation requirements with and without a space station, the short-lifetime missions were retained for transportation requirement comparison, but in actuality their short orbit lifetime without a space station would be unacceptable.

Technology Development Missions

- Original set of 76 candidate missions was cut to 33 by screening and budgetary considerations.
- Space structures and optics, flight controls, fluids, robotics, and energy technology identified as important.
- Space station is enabling for 43% of these missions.
 - Size and handling
 - Support equipment needs
 - Short life time in orbit unless attached to space station
 - Extensive crew involvement, e.g. for construction, calibration and test.

Model of large antenna

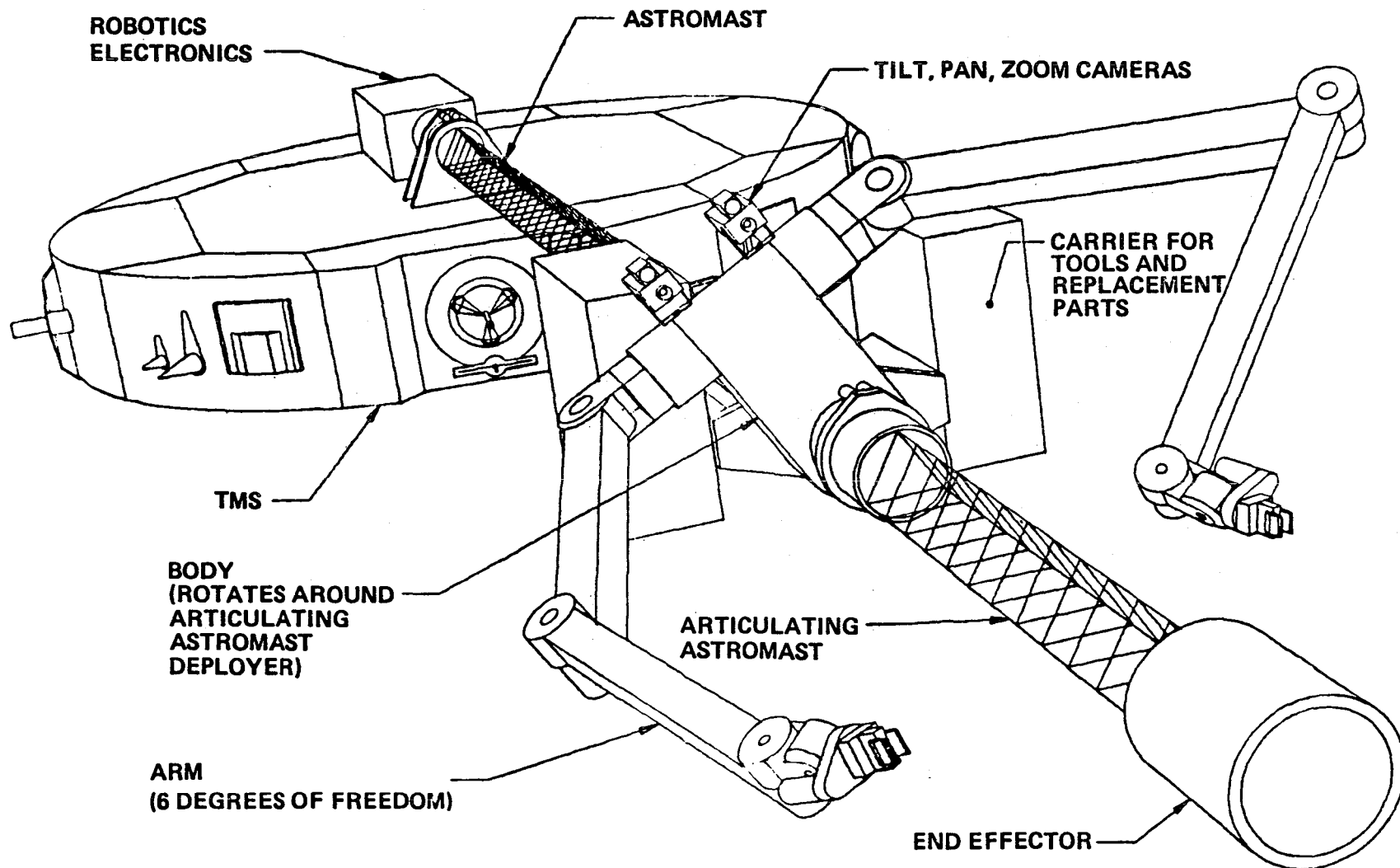


SPACECRAFT ROBOTICS SERVICER

Included in the mission set requiring space station because of the crew involvement time was a group of missions exemplified by the spacecraft robotic servicer illustrated here. These missions included spacecraft robotic servicing technology development, spacecraft and upper stage servicing and integration, and maintenance activities. They would develop a blend of crew use and automation techniques to accomplish effective servicing.

Spacecraft Robotic Servicer

SS-568



THE PAYOFF

Accumulating earth observation instruments through servicing will lead to better understanding of the earth's climate, atmosphere, oceans and biosphere. These are issues of enormous long-range economic importance, such as CO₂, climate and sealevel; such as long-range climatic evolution; is the earth headed for another ice age or could it become once again semi-tropical as in eons past? What is the mechanism of sun/earth coupling? Do sunspots influence climate? Can food production keep up with earth's growing population? Are the oceans in danger of being severely damaged by pollution as some people fear?

Servicing and accumulation of astrophysics instruments will permit a better understanding of our solar system and universe. Although not of immediate, direct, practical application, this is of enormous cultural value.

Freedom from gravity forces provides an added dimension for life sciences and materials research. The potential payoffs for life science research are much broader than long-term spaceflight. This research could lead to important new understandings of basic biological processes and development, things of scientific and practical value.

Research has demonstrated the importance of lack of gravitational forces in certain materials processes. Economic benefits derivable from materials processing in space are potentially large. The main use of the space station is in research and development of new processes, products and materials. A space station could lead to the industrialization of low earth orbit with very large economic returns.

A space station will enable much more rapid progress at the cutting edge of high technology industry. Some of the payoffs are indicated on the facing page. Preserving U.S. technological supremacy is a very important national goal that can be enhanced to by a manned presence in low earth orbit.

Finally, a space station offers higher productivity for space transportation.

The Payoff

- Better understanding of Earth's climate, atmosphere, oceans, biosphere.
 - CO₂, climate, and sea level
 - Ice age versus semitropical
 - Food production and health of our oceans
 - Sun/earth coupling
- Better understanding of our solar system and universe
 - Beginnings and endings
 - High energy processes and new phenomena
- An added dimension for life sciences and materials research
- Cutting edge of high-tech. industrial technology
 - Pharmaceuticals: New drugs and biological products
 - Semiconductors: Ultrahigh speed and electro-optical computers; next-generation sensors
 - "Super" glasses for optical fiber and laser applications
 - Large antennas and optics in space
 - Robotics
- Higher productivity for space transportation

} Trillion-dollar issues

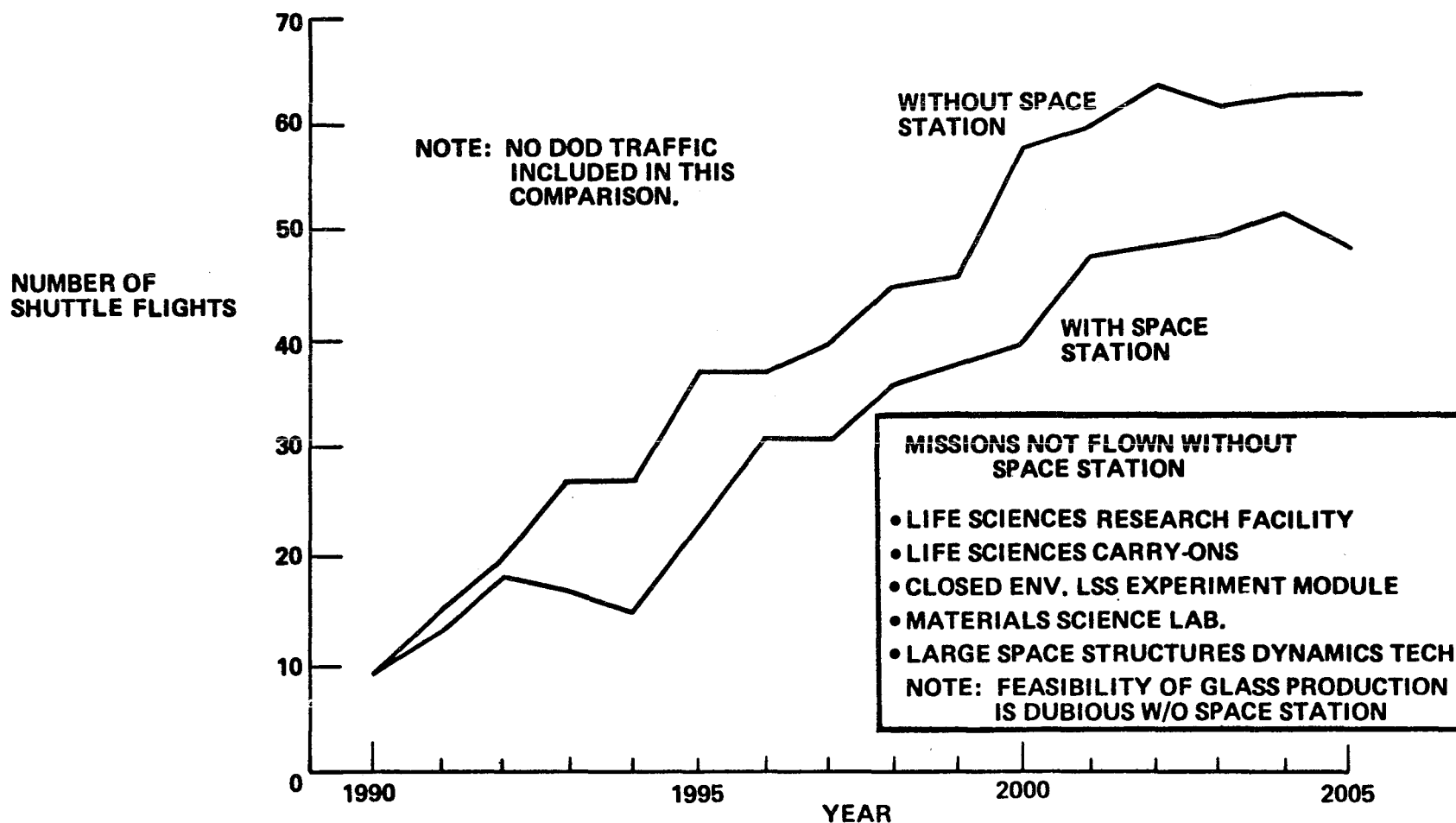
SHUTTLE TRAFFIC MODEL RESULTS

In order to estimate of the quantitative benefit of the space station to space transportation operations, a no-space-station scenario was created. In this comparison scenario, all crew involvement in mission operations was deleted to avoid unrealistic stressing of the space transportation system. There are other missions probably impractical without a space station, such as some of the technology development, science and commercial applications involving large, lightweight structures. These were included, in the scenario to obtain the best available direct comparison.

DOD shuttle utilization is not included in the traffic model results shown.

The availability of the space station reduces the number of shuttle flights required to service the mission model by 10 to 12 flights per year.

Shuttle Traffic Model Results

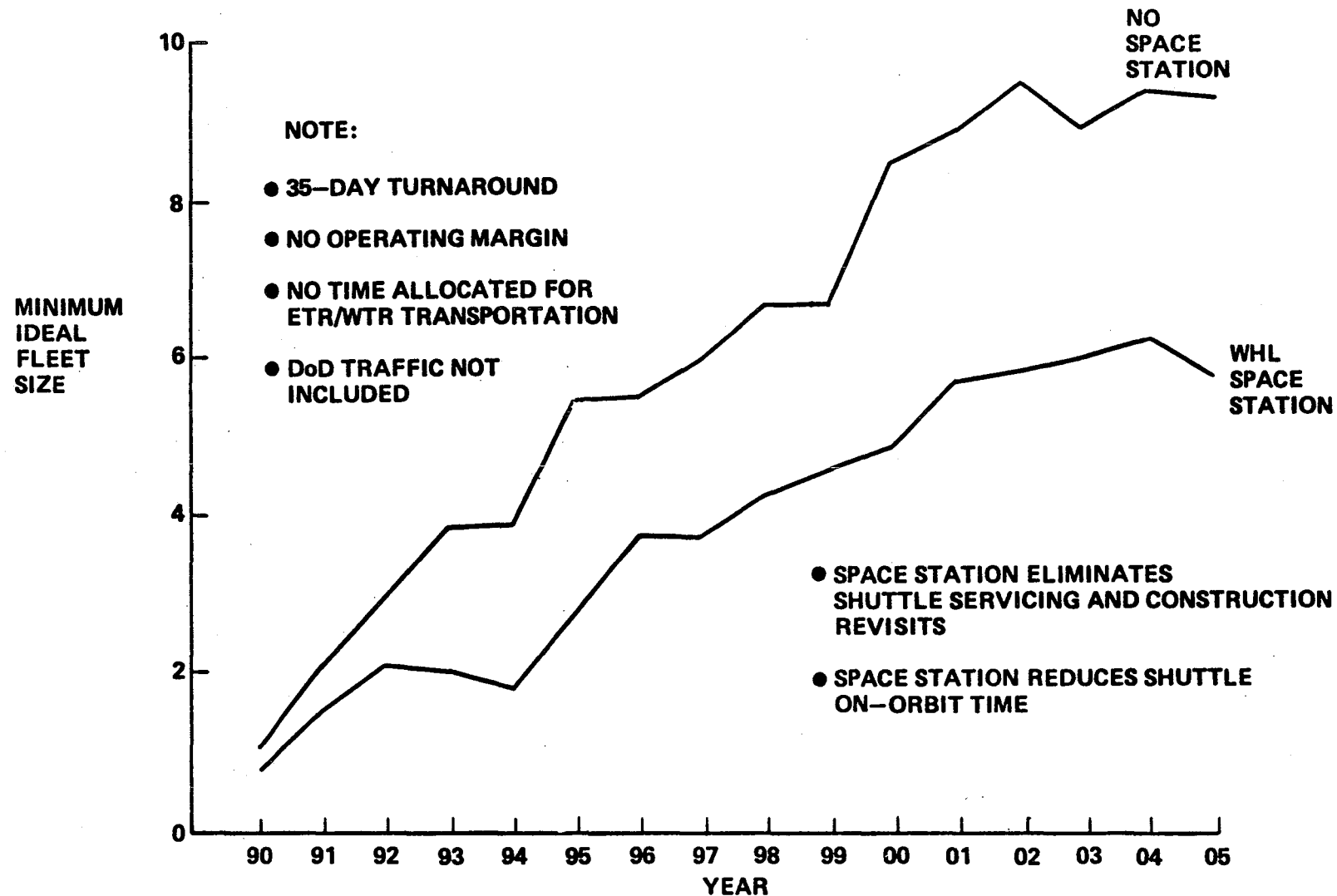


SHUTTLE FLEET PRODUCTIVITY IMPROVEMENT

Requirements on the shuttle fleet imposed by not having a space station include additional stay time on orbit as well as additional flights. Consequently, the number of vehicles required to service the mission model increases from roughly six to roughly nine. This indicates that the space station offers about 50% improvement in the shuttle fleet productivity. The fleet size indicated on the facing page, is based on a 35 day turnaround with no operating margin, no time for moving shuttle orbiters between east and west launch sites and does not include impact of DOD traffic.

These traffic requirements are heavily driven by the commercial materials processing in space mission requirements. That category of activity accounts for most of the growth in flight rate and fleet requirements from the 1990 to post-2000 timeframe.

Shuttle Fleet Productivity Improvement



SPACE STATION ECONOMIC BENEFITS

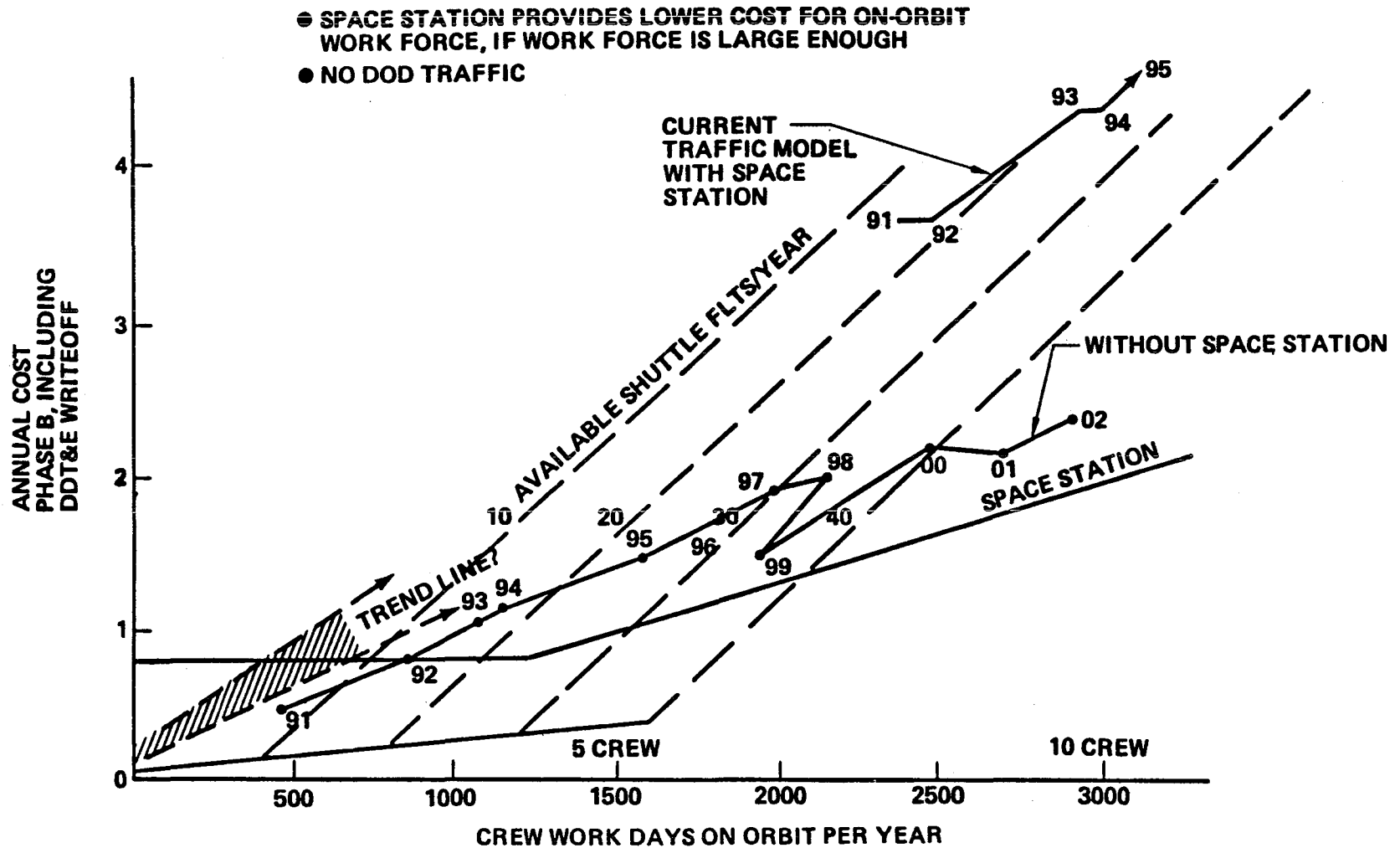
The cost of crew workdays on orbit varies widely depending on the circumstances under which the workdays are provided. If worktime on orbit can be provided simply by keeping the space shuttle aloft after it has delivered a payload, the cost is relatively low: the cost of retaining the shuttle on orbit at roughly a million dollars per day. If additional shuttle flights must be scheduled simply to provide additional crewtime on orbit, then the crewtime cost must amortize the cost of the flights and becomes at least 10 times as expensive.

Comparing with a space station, we found that a minimum space station program provides accommodations for approximately 5 crew. One person would (on the average) be involved in operating the space station and not counted as useful workforce. This minimum space station would cost between 800 million and a billion dollars a year to support, including a 5-year amortization of initial costs, shuttle transportation costs to service the space station plus mission control costs.

This cost is essentially fixed, no matter how small the actual requirements for space crew worktime. Therefore, for minimal on orbit crewtime the shuttle offers the less expensive solution. However, if the time required on orbit exceeds a certain amount relative to the number of available shuttle flights per year, a space station becomes the less expensive solution.

Crew workload results with and without space station are cross-plotted on the shuttle cost characteristic curves. If a space station is available, much crew worktime is invested in mission experiments and mission operations. Shuttle manifesting is relatively efficient and fewer flights are required. The second curve shows estimated crew worktime without the space station. Shuttle flights for this mission model were not counted if they were scheduled purely to provide additional crewtime on orbit. In either case, the crewtime-versus-traffic trend is in the region where the space station is the cost-effective solution.

Space Station Economic Benefits



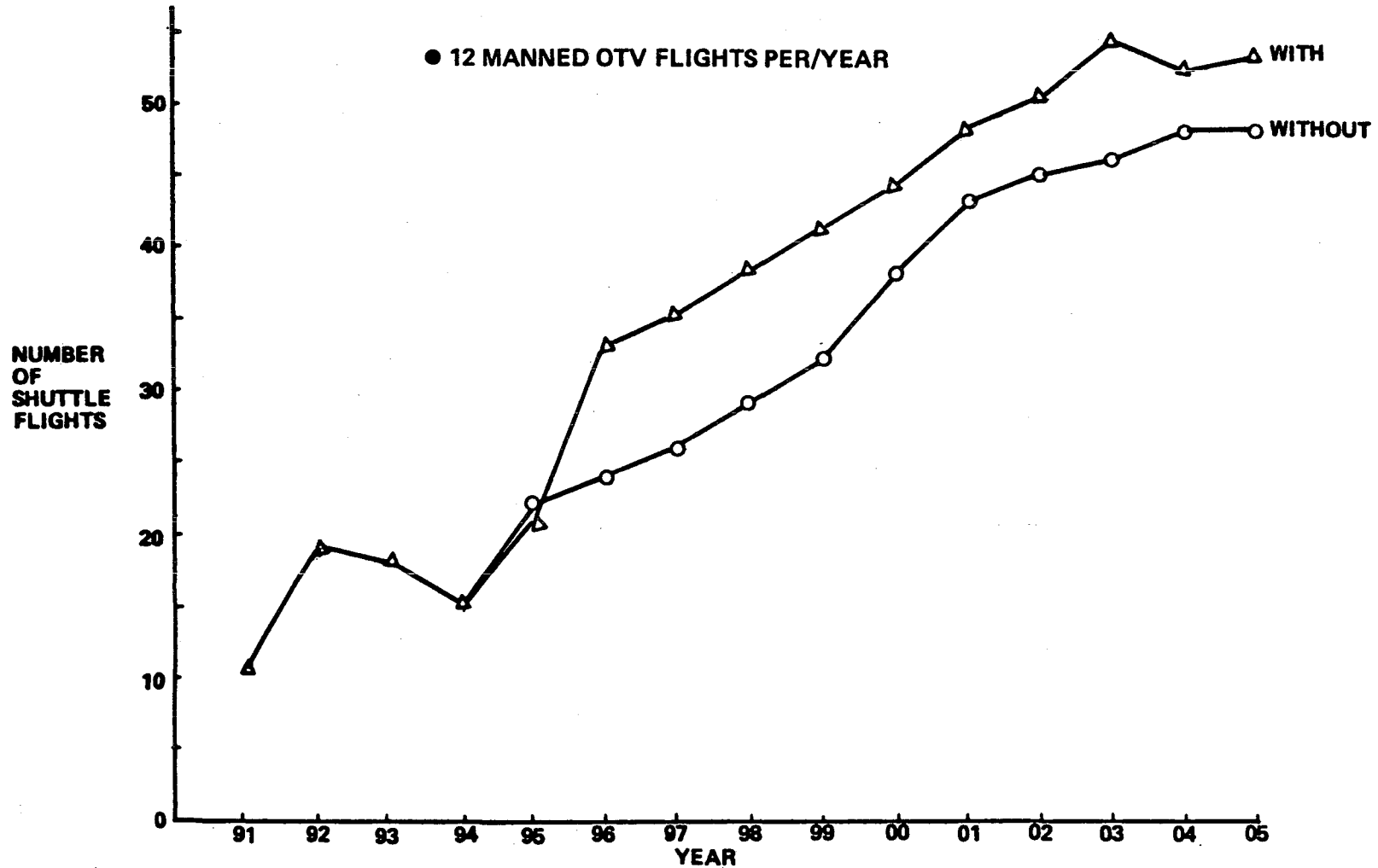
MANNED GEO OPERATIONS IMPACT ON TRANSPORTATION OPERATIONS

If a space station is available for space-basing a manned OTV, the impact of manned GEO operations on shuttle flight traffic is modest. The effect for 12 manned OTV flights per year is shown on the facing page. The number of additional shuttle flights required to support this level of manned OTV operations ranges from 10, down to roughly 5 or 6 as other traffic increases. Heavy propellant delivery requirements for the manned OTV operation present opportunities for mixed manifesting of propellant delivery and payload delivery, thus improving the shuttle mass load factor.

The results shown included the use of shuttle external tank scavenging to improve propellant delivery efficiency.

Manned GEO Operations Impact on Transportation

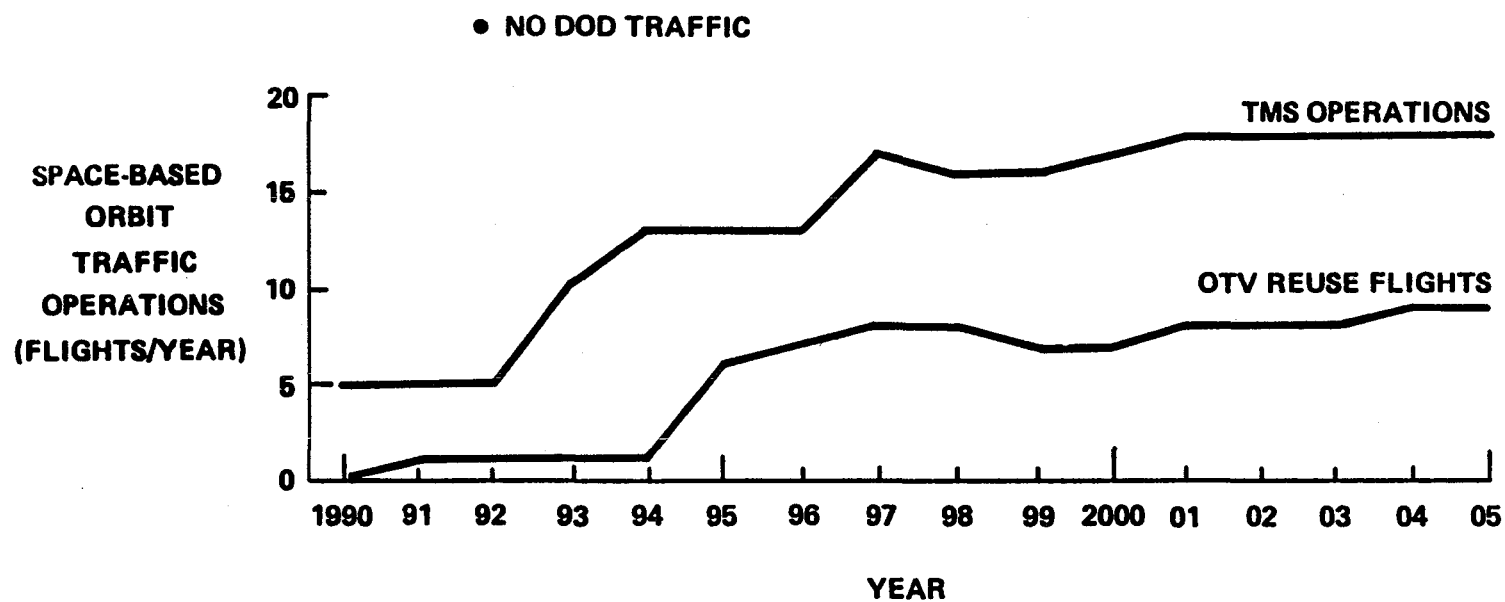
SS-567



TMS AND OTV OPERATIONS

The satellite and commercial platform servicing included in our mission model results in a greater number of TMS operations than OTV flights. The TMS operations require relatively little propellant compared to OTV operations; the typical TMS operation consumes less than 1,000 kilograms of propellant.

Space Based Traffic Model



SPACE STATION TRANSPORTATION INTERRELATIONSHIPS: LAUNCH VEHICLES

A space station relieves the shuttle of flights dedicated to orbital servicing. Manifesting can be more efficient. Less time for the shuttle on orbit is required. These all add up to roughly a 50% improvement in shuttle fleet productivity. A significant contribution to this is the eventual use of space based upper stages to aid in meeting shuttle manifesting mass and center of gravity constraints by permitting mixed propellant and payload delivery.

We did not analyze use of shuttle-derived cargo vehicles in these scenarios. Our results indicate three appreciable benefits. Most significant will be shuttle fleet relief and provision of operating margin. Many of the payloads delivered to the space station could be delivered by unmanned launch vehicle with TMS operations to secure the payload and bring it to the space station. In scenarios with a high level of OTV or manned OTV activity, benefits would accrue from use of the shuttle-derived vehicle for propellant delivery.

We did not identify oversize payloads, but anticipate that the future will lead to some.

We did not identify specific heavy lift requirements that would set a firm requirement for a lift capability greater than the capability of the shuttle. The shuttle derived cargo vehicle should be sized to maximize fleet relief, operating margins, and cost-effectiveness.

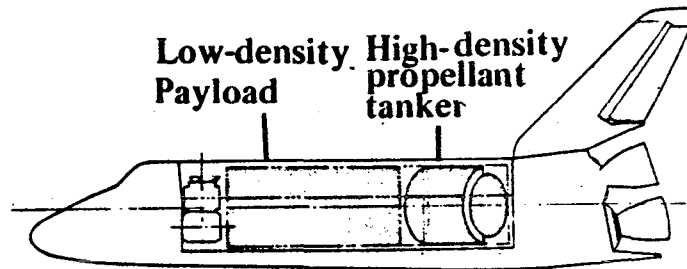
Space Station/Transportation Interrelationships

Launch Vehicles

- Shuttle

- Relieved of flights dedicated to orbital servicing
- More efficient manifesting
- Less time on orbit

Roughly 50% improvement in fleet productivity



Space-based upper stage aids manifesting—mass & CG by permitting mixed propellant/payload delivery

- Shuttle-Derived Cargo Vehicle

- Fleet relief and operating margin
- Propellant and oversize payload delivery
- No specific heavy-lift requirement identified

SPACE STATION/TRANSPORTATION INTERRELATIONSHIPS: UPPER STAGES

There are several existing, planned, and contemplated upper stages for space transportation operations. These are summarized on the facing page. Their typical applications are noted and potential space station applications are described. A checkmark signifies likely benefit; a bullet signifies dubious or uncertain benefit.

It is important to recognize the potential benefit of assembly to help shuttle CG manifesting. If several small upper stages such as PAMs and SSUSs, with their payloads, are loaded in the shuttle payload bay, a CG problem may exist. However, if the relatively dense propulsion stages were grouped in the back of the payload bay and the less dense payloads in front, the CG problem would be alleviated.

The TMS is very important to the servicing aspect of space station operations, and serves other functions.

We see eventual evolution to a reusable space-based OTV at which point the space station would provide the services indicated.

SS-644 Space Station/Transportation Interrelationships

Upper Stages

<u>Upper Stage</u>	<u>Typical Applications</u>	<u>Potential Space Station Application</u>
PAMs and SSUSs	Geo transfer payload delivery	✓ Holding for longitude drift ✓ Assembly to help shuttle CG • On-orbit storage?
IUS	Geo payload delivery	• Payload deploy or assembly?
CENTAUR	Geo/planetary payload delivery	
TOS	Geo transfer payload delivery	✓ Holding for longitude drift ✓ Assembly to help shuttle CG
Reusable TMS	Free-flyer science subsatellite	✓ Other leg of mission
	Satellite delivery	✓ TMS control/basing
	Satellite servicing-manned or unmanned	✓ TMS/servicing operations base
	Low-thrust Geo transfer delivery	✓ Spacecraft deploy/assembly/checkout
Reusable Ground-based OTV	Geo transfer or GEO delivery	✓ Hold for shuttle retrieval ✓ Spacecraft deploy/assemble/checkout
Reusable space-based OTV	Geo transfer or Geo delivery	✓ Space Basing:
	Manned Geo Access	Propellant storage and transfer OTV maintenance Crew cab maintenance ET scavenged propellant storage

CRITERIA FOR ASSIGNED CREW TASKS

The crew demand results described earlier were derived by making crew task assignments to each payload and mission on an individual basis. The criteria are summarized on the facing page. Crew involvement in missions was assigned only if stated as needed by the mission user or mission investigator. Payload and mission servicing were normally assigned crew involvement because most such servicing will be unscheduled maintenance. Similar considerations apply in the construction of large space structures inasmuch as each construction job will be different than its predecessors. Upper stage turnaround and materials processing development require specific human skills not expected to be available through automation or robotics in the timeframe of interest.

Strong dependence on automation for routine tasks and functions in space station housekeeping was assumed in order to free up crewtime for useful tasks that could not be automated.

Why Man?

Criteria for Assigning Crew Tasks

PRINCIPAL TASKS	RANGE OF MANDAYS/ TASK	USER PREFERENCE	IMPRACTICAL TO AUTOMATE	
			NO LEAD TIME	TASK REQUIRES HUMAN VISION, JUDGMENT, OR MANIPULATIVE SKILLS
CARGO OFFLOAD	1 – 2			X
SCIENCE MISSION INVOLVEMENT *	5 – 365	X		INTERACTIVE RESEARCH
PAYLOAD/MISSION SERVICING *	1 – 80	X	UNSCHEDULED MAINTENANCE	X
CONSTRUCTION OF LARGE SPACE STRUCTURES PAYLOAD DEPLOY ASSIST	1 – 300		TROUBLESHOOTING	TEST AND CHECKOUT
UPPER STAGE TURNAROUND	5 – 80			X
MATERIALS PROCESSING DEVELOPMENT	90 – 365			INTERACTIVE RESEARCH

* AUTOMATION ASSUMED FOR ROUTINE TASKS AND FUNCTIONS

ROBOTICS AND MACHINE INTELLIGENCE EVALUATION

We prepared a forecast of robotics and machine intelligence capabilities in the mid 1990's in order to judge the validity of the criteria that we used to assign crew tasks to missions and payloads. It is presented on the facing page. We concluded that the task assignment criteria were valid. Crew functions assumed in this study could not practically be accomplished by robotics or automation in the timeframe of interest.

Robotics and Machine Intelligence Evaluation

	Now	Mid-1990's Projection
Natural Language Understanding	Voice word recognition for program control and data entry Limited "recognition" of simple sentence meaning from keyboard input	English programming and data entry with predefined vocabulary and subject matter Some Q&A capability to ensure correct interpretation No ability to deal with unexpected
Dexterity	Simple graspers with tactile feedback Reasonable analogs of human arm Very "weak" for their mass; slow	Reasonable analogs of human hands & arms Improvements in strength and speed but still far inferior to human
Mobility	Experimental—in practical applications, work is brought to machine	Practical in structured environment; e.g., flat factory floor with negotiable obstructions
Eye-Hand Coordination	Recognition and pick-up of isolated geometric objects	Recognition and manipulation of practical objects; e.g., machine and electronics parts Doubtful ability to carry out complex tasks such as installing a connector
Creative Thinking and Judgment	No capability	Doubtful. Requires conceptual breakthrough followed by extensive R&D

CONCLUSION: The tasks we have assigned to crew are not practical for robotics/automation in the time frame of interest.

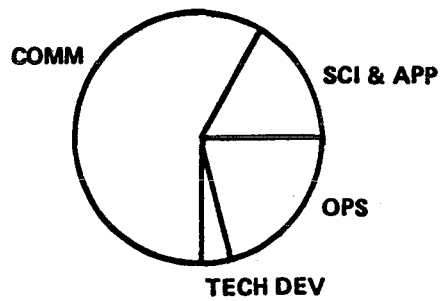
CREW NEEDS—LOW INCLINATION

Our automated analysis procedure summed the crew needs by mission type and by function. For low inclination missions, dominant crew involvement needs were for servicing and conduct of commercial missions. Crew use in science and applications was primarily for mission involvement, mainly in life sciences. Operations involvement included shuttle and space transportation servicing.

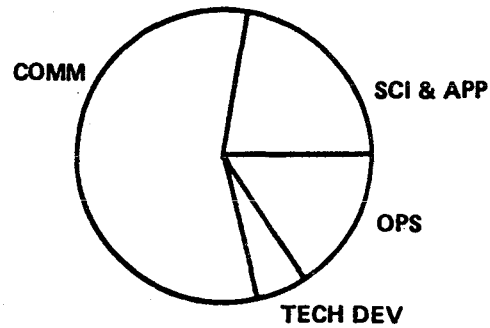
Crew involvement by function was predominantly servicing, and secondarily mission operations or transportation operations depending on the timeframe of interest. The construction activity was the least of the various crew needs identified.

Crew Needs - Low Inclination

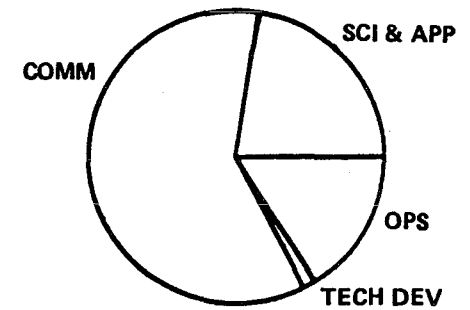
BY MISSION TYPE



TOTAL = 5430
YEAR 1995

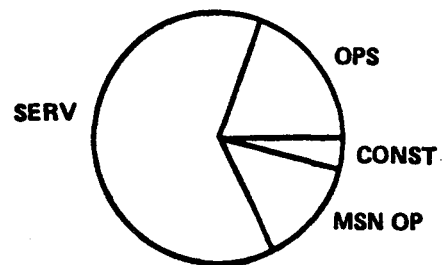


TOTAL = 7428
YEAR 2000

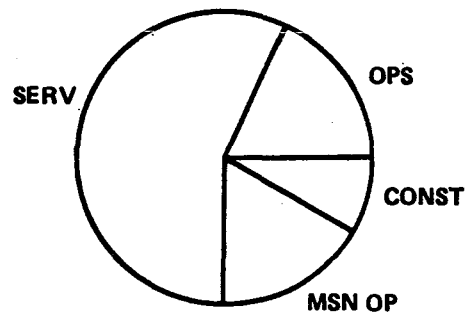


TOTAL = 7728
YEAR 2005

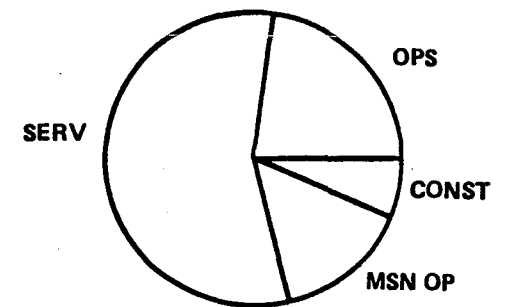
BY FUNCTION



TOTAL = 5430
YEAR 1995



TOTAL = 7428
YEAR 2000



TOTAL = 7728
YEAR 2005

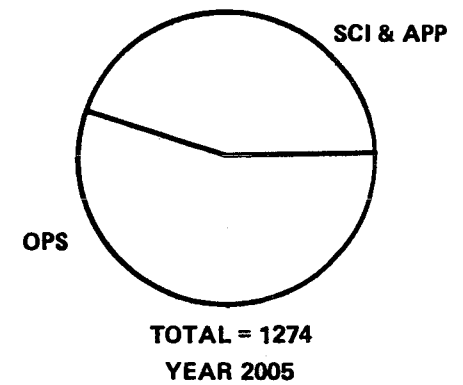
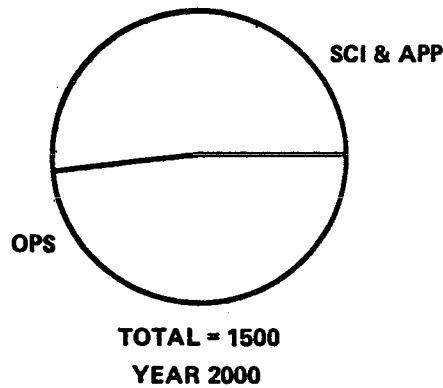
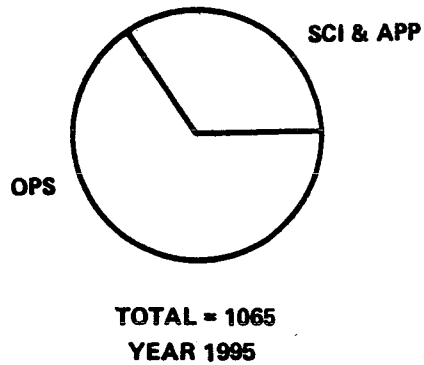
TOTAL = MANDAYS/YEAR

CREW NEEDS—HIGH INCLINATION

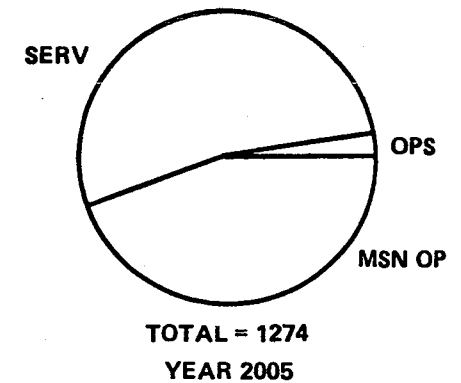
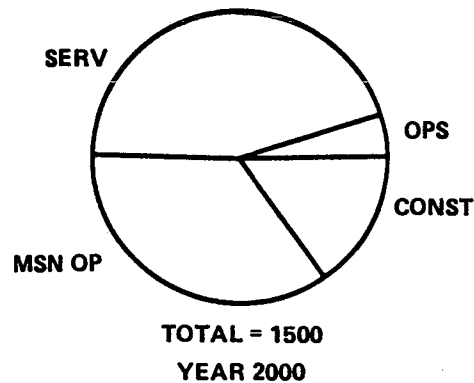
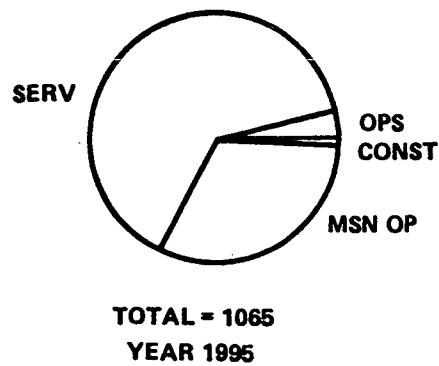
This figure presents a summary of the same results for the high inclination mission. Again servicing predominated as a mission involvement. The high inclination crew needs in total man days per year are approximately 1/5 of those at the low inclination.

Crew Needs - High Inclination

BY MISSION TYPE



BY FUNCTION



TOTAL = MANDAYS/YEAR

BENEFITS OF MANNED PRESENCE

To recap and summarize the benefits of manned presence: to perform new functions and missions not practical to automate and functions that will improve productivity of utilization of space in the future. The facing page lists the principal functions, the benefits and certain related issues.

Benefits of Manned Presence

Function	Benefit	Related Issues
Maintenance and Repair	<ul style="list-style-type: none"> • Reduced equipment cost • Enhanced availability and life 	<ul style="list-style-type: none"> • Capturing cost savings potentials
Real-time mission involvement	<ul style="list-style-type: none"> • Reacting to unexpected or transient events • Discovery, insight, & understanding 	<ul style="list-style-type: none"> • Designing mission and instruments to take advantage
Lab operations	<ul style="list-style-type: none"> • Difficult or impossible to automate • Research progress not paced by shuttle reflight schedule 	<ul style="list-style-type: none"> • Lab equipment at space station • Crew skills
Construction, Assembly, Test Checkout, Modification of large systems	<ul style="list-style-type: none"> • Difficult or impossible to automate • Simplify designs compared to complex deployment • Stiffen structures • Final test and correction in space 	<ul style="list-style-type: none"> • Role of EVA • Design to capture benefits • Low-thrust transfer to final destination

NEW INSIGHTS TO SPACE STATION MISSION NEEDS

The facing page summarizes the new insights to space station mission needs gained from the present study.

The magnitude of latent commercial interest in materials processing was surprising to us. This interest is presently deterred by perceived uncertainties and risk, and the perception of many years' further research required before major payoffs. It is likely that initial commercial marketing successes for even one space produced material will very quickly transform most of this latent interest into active interest.

Potential benefits for a space station to large commercial communications satellite were identified and validated by RCA.

The significance of servicing benefits for science, providing the opportunity to accumulate rather than simply replace space science assets, offers improvement in space science productivity.

The benefits of a small high inclination space station for earth observation missions and the importance of reaching higher altitudes for a low inclination space station to service astrophysics missions were both new findings. Further, it now appears practical to achieve the desired altitudes by direct-injection space shuttle operations.

We quantified needs for tools, equipment, and laboratories to realize the benefits of manned presence and identified three distinct laboratory module functions. Power needs estimates are much higher than perceived previously.

Finally, we accomplished an initial specific quantification of benefits of manned presence.

New Insights to Space Station Mission Needs

- **Magnitude of latent commercial interest in materials processing—deterred by uncertainty of access and timing.**
- **Acceptance of benefit of space station to large commercial satellites.**
- **Significance of servicing cost-benefits for science—accumulation rather than replacement of assets.**
- **Importance of high-inclination missions for earth observation**
- **Importance of higher altitudes (500 km versus 370 km) for astrophysics missions.**
 - **Accessible by direct injection.**
- **Importance of tools and equipment to realize benefits of manned presence.**
- **Need for three distinct lab module functions.**
 - **Science operations**
 - **Vivarium**
 - **Diagnostics laboratory**
- **Magnitude of electrical power demand**
- **Initial quantification of benefits of manned presence.**

NEEDS FOR ATTRIBUTES AND ARCHITECTURAL CHARACTERISTICS

The mission needs results pointed out a number of specific needs for space station attributes and architectural characteristics. These are summarized on the facing page.

Needs for Attributes and Architecture Characteristics

Need	Source or Rationale
Fly in low inclination low earth orbit	Operations missions; servicing astrophysical observatories.
Fly in high inclination low earth orbit	Scientific and national security missions
Fly either earth-oriented or inertial	Science missions
General purpose lab plus returnable lab	Science missions
Formation fly with free-flyers	Science and commercial missions
Generous workshop and warehouse space	Need to minimize transportation charges for diverse science missions
Mobile crane or RMS	Operations and construction missions
Hangars	Operations and national security missions
Multiple berthing ports	Mission diversity
Securable control room	Accommodation of classified missions
Autonomy	National security missions
Minimum resupply	National security missions
Safe haven and redundancy	Crew safety
Separate work and free-time areas	Crew well-being
Adequate electric power	Aggregated user requirements

MISSION INFLUENCES ON ARCHITECTURE

Mission needs indicated that we should have both low inclination and high inclination capability. The high inclination missions use the crew mainly for instrument repair and secondly for mission operations. The space station serves primarily as an instrument platform and needs a crew of four.

Low inclination missions were much more diverse requiring a variety of crew involvements as noted on the facing page. We observed needs for crews as large as 20 in the post 2000 timeframe. Accommodation of this number of people may best be achieved by eventually having two space stations in low inclinations, one aimed primarily at operational needs and the second aimed at scientific needs.

The high inclination mission is subject to solar flare radiation in the event of a solar flare and the system architecture needs to provide space for a radiation shelter for the high inclination mission.

Mission Influences on Architecture

- Missions are clustered around sun-synch and low inclinations. Architecture needs to accommodate both.
- High inclination missions use crew mainly for instrument repair; secondarily as mission operator. Space station is instrument platform. Crew of 4.
- Low inclination missions are diverse. Variety of crew involvements. Space station is:
 - Instrument platform
 - Laboratory
 - Operations and servicing base
 - Construction facility
- Crew size starts at 4 – 6, grows to 20.
- Flexible, modular architecture needed to satisfy diversity of needs.
- High inclination missions need radiation shielding.

LOW INCLINATION NEEDS SUMMARY

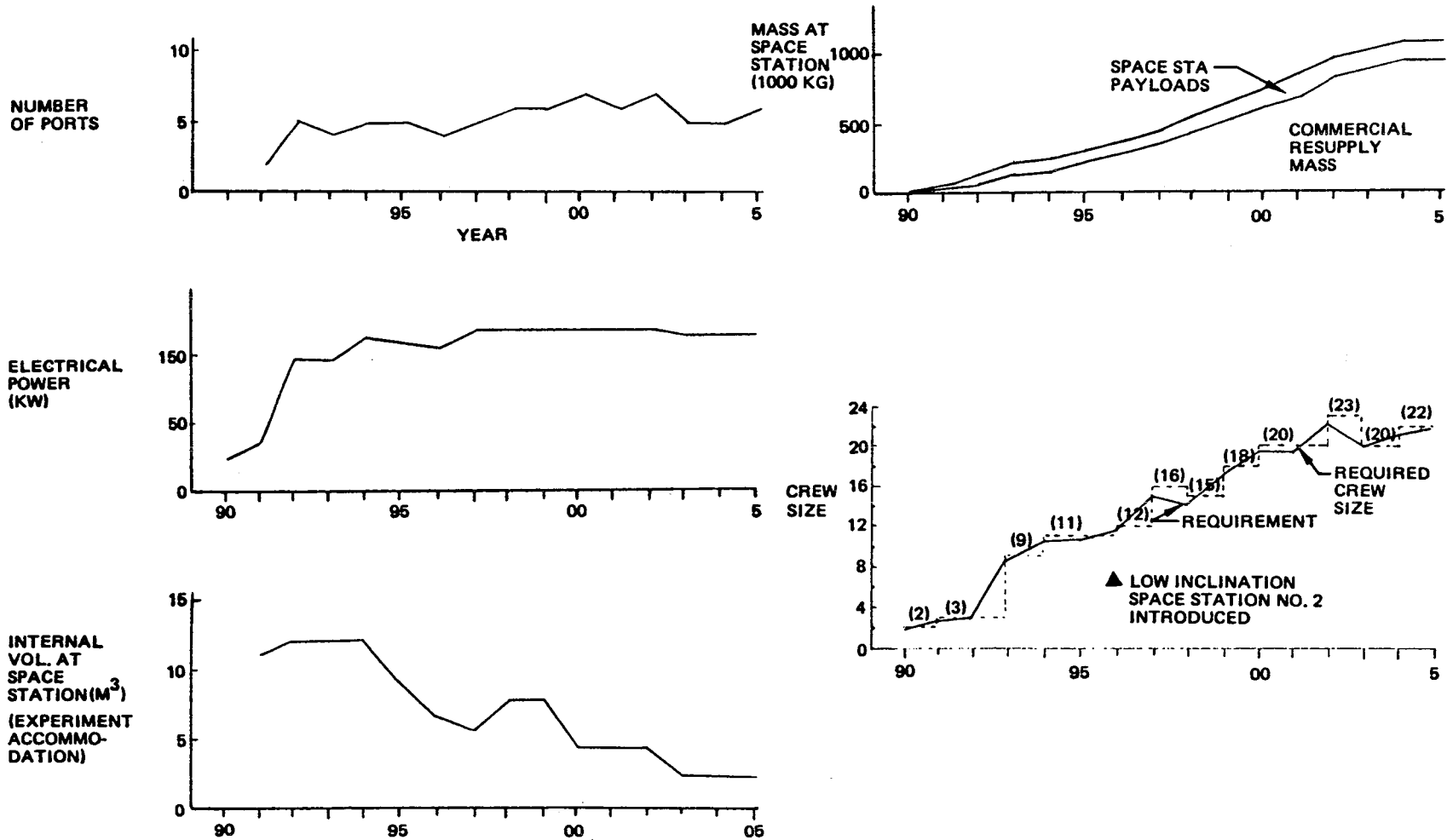
The next two pages summarize the space station mission needs for low and high inclination missions for the mission-driven scenario.

A second scenario, space-station-program-limited, deferred some of the missions to reduce the rate of build-up of power and crew support requirements. Thus the accommodation of space station mission needs may be limited by the space station program rather than by the evolution of mission needs.

We did not make specific estimates of the data requirements for space station because we do not feel that the input data are sufficiently valid to set a specific requirement for data handling capability. The appropriate program approach appears to be to providing the data handling capability permitted by the state-of-the-art, and not being driven by aggregated user requirements which may be off by an order of magnitude at the present state of understanding.

Low Inclination Needs Summary (Scenario A - Mission Driver)

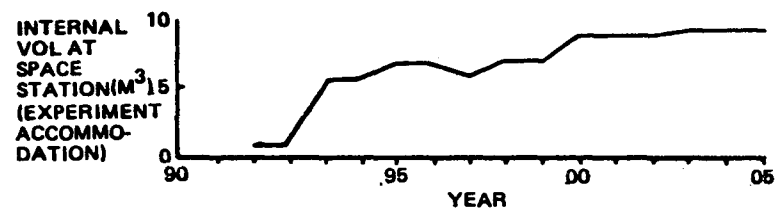
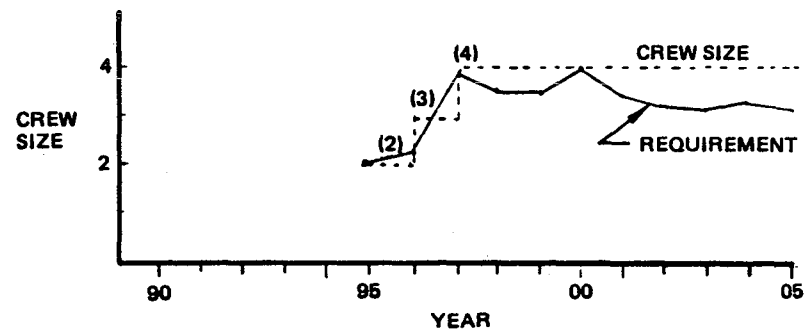
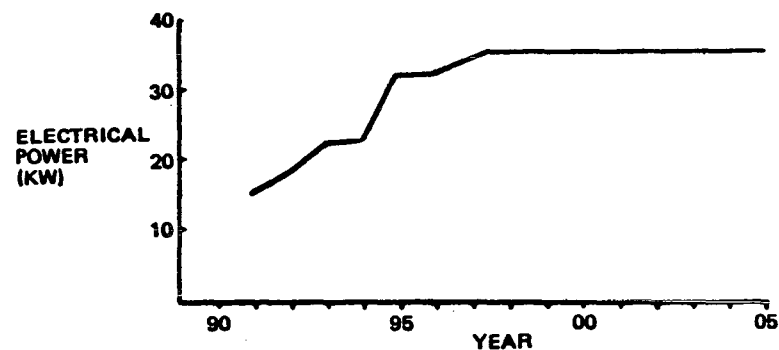
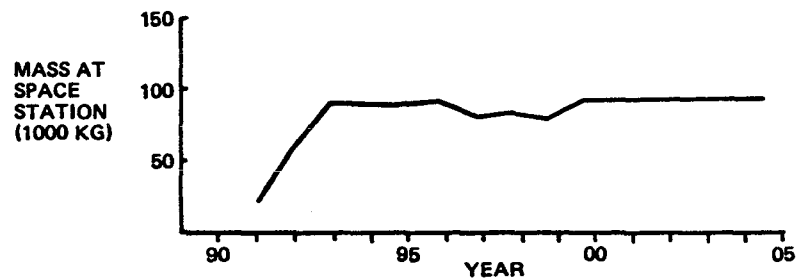
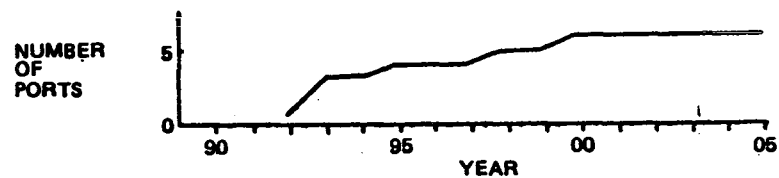
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High Inclination Needs Summary

Scenario A - Mission Driver)

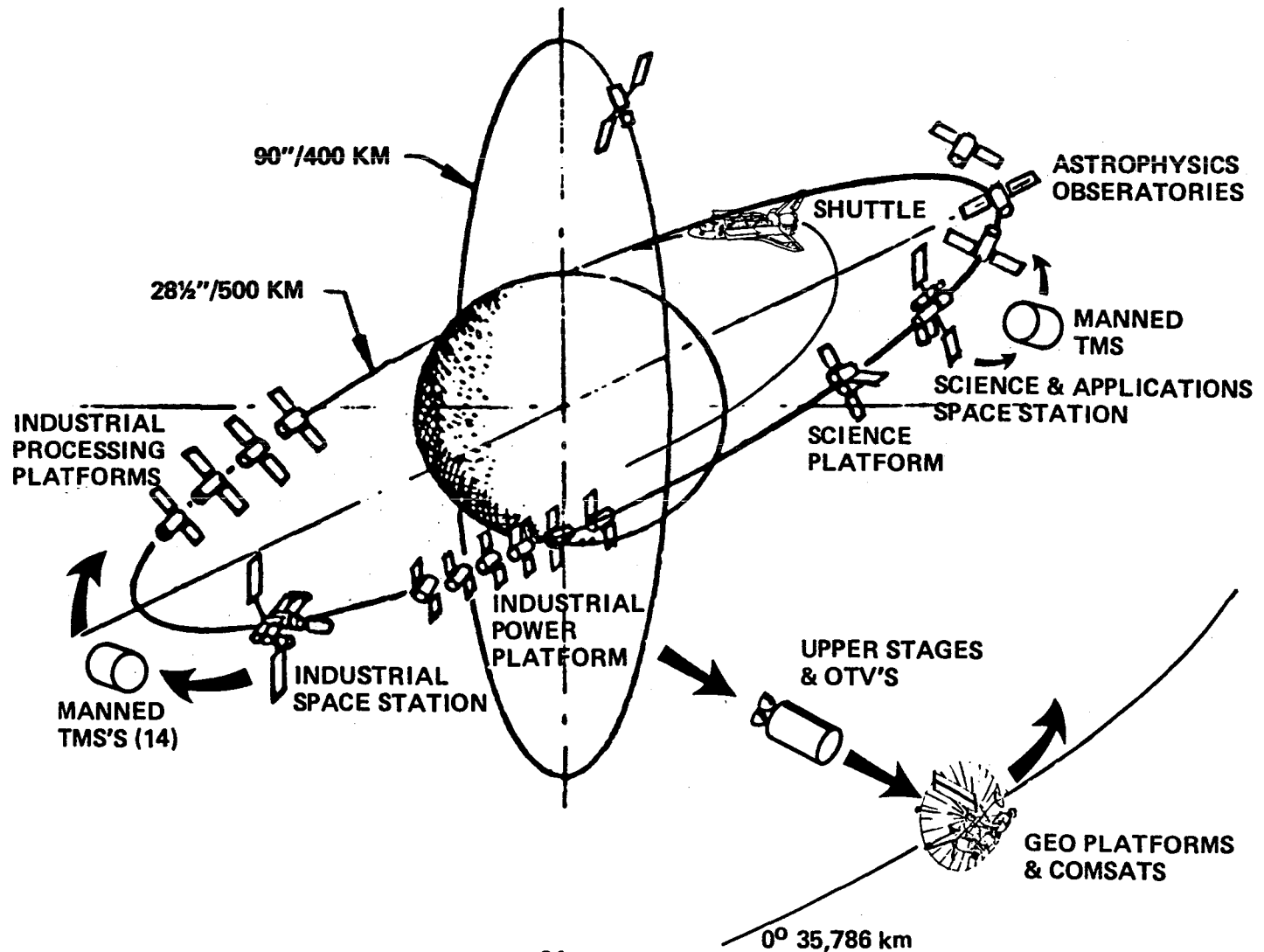


EVENTUAL ARCHITECTURE YEAR 2005

The overall system architecture includes space stations at low and high inclinations with several commercial micro-gravity production platforms, a cluster of astrophysics free-flyers and an astrophysics platform. In addition, OTV's are used to deliver payloads in high altitude orbits and TMS's are used for relative access between the space stations and formation flying vehicles in low inclination orbit.

The shuttle provides Earth-to-space and return transportation.

Eventual Architecture - Year 2005 (Scenario A - Mission Driven)



PROJECTED STS LIFT CAPABILITY

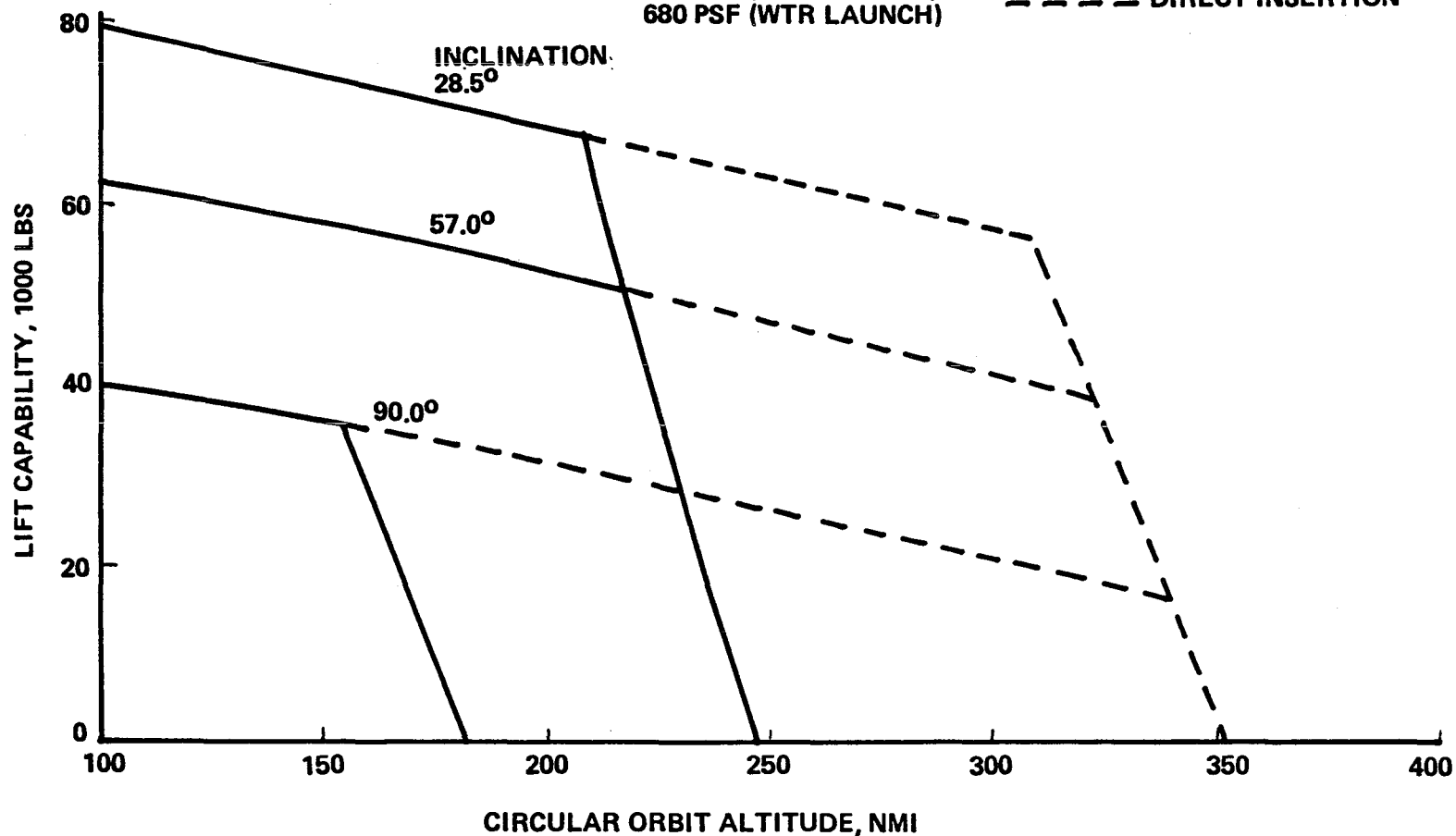
The projected STS payload lift capability on the facing page was supplied to us by JSC. The use of direct insertion increases the altitude capability at nearly full payload to the range of current interest. (500 kilometers is 270 nautical miles.)

For high-inclination missions, the space station altitude will be limited to about 400 km (216 n. mi.) in order to lift payloads up to about 30,000 lbs.

Projected STS Lift Capability

- 109% SSME POWER LEVEL
- NOMINAL TRAJECTORY SHAPING
- FILAMENT WOUND HPM
- PAYLOAD DEPLOY MISSION
- JANUARY LAUNCH
- MAXIMUM Q – 700 PSF (ETR LAUNCH)
680 PSF (WTR LAUNCH)

— NOMINAL INSERTION
- - - DIRECT INSERTION



ORBIT ALTITUDE CONSIDERATIONS

In earlier studies, the space station altitude was limited to 370 kilometers by shuttle performance considerations. Since that time, NASA investigation of direct insertion operations for the space shuttle has projected a capability to operate a low inclination space station at about 500 kilometers altitude and a high inclination station at about 400 kilometers altitude. The higher altitude is very important for servicing of astrophysics missions since the space station and these missions must fly at the same altitude to provide on-demand servicing. The higher altitude reduces drag by roughly an order of magnitude as compared to the lower altitude considered earlier. Consideration of the selection of orbit makeup propulsion technology should be opened for reconsideration.

Orbit Altitude

SOC Studies:

Altitude was limited to 370 km by shuttle performance without OMS kit.

New Options:

	<u>East</u>	<u>Polar</u>
Direct insertion –	500 km	400 km

TMS & crew cab – any altitude permitted by radiation (about 600 km).

Space station must be at same altitude as serviced spacecraft for on-demand servicing.

500 km is above most UV air glow – important for space telescope.

Greatly enhances space station utility for observatory servicing.

500 km reduces drag by an order of magnitude compared to 370 km.

Orbit makeup could use resistojet/ECLSS surpluses
Supplement with O₂/H₂ for densest atmosphere.

PROPELLANT USAGE VERSUS ALTITUDE

This figure is modified from the Space Operation Center orbit selection results. It represents an eight man space station with approximately 50 kilowatts electrical power capability. During the SOC studies the shuttle performance was limited to 370 kilometers without an OMS kit (direct insertion was not considered). The SOC nominal altitude is spotted on the curve.

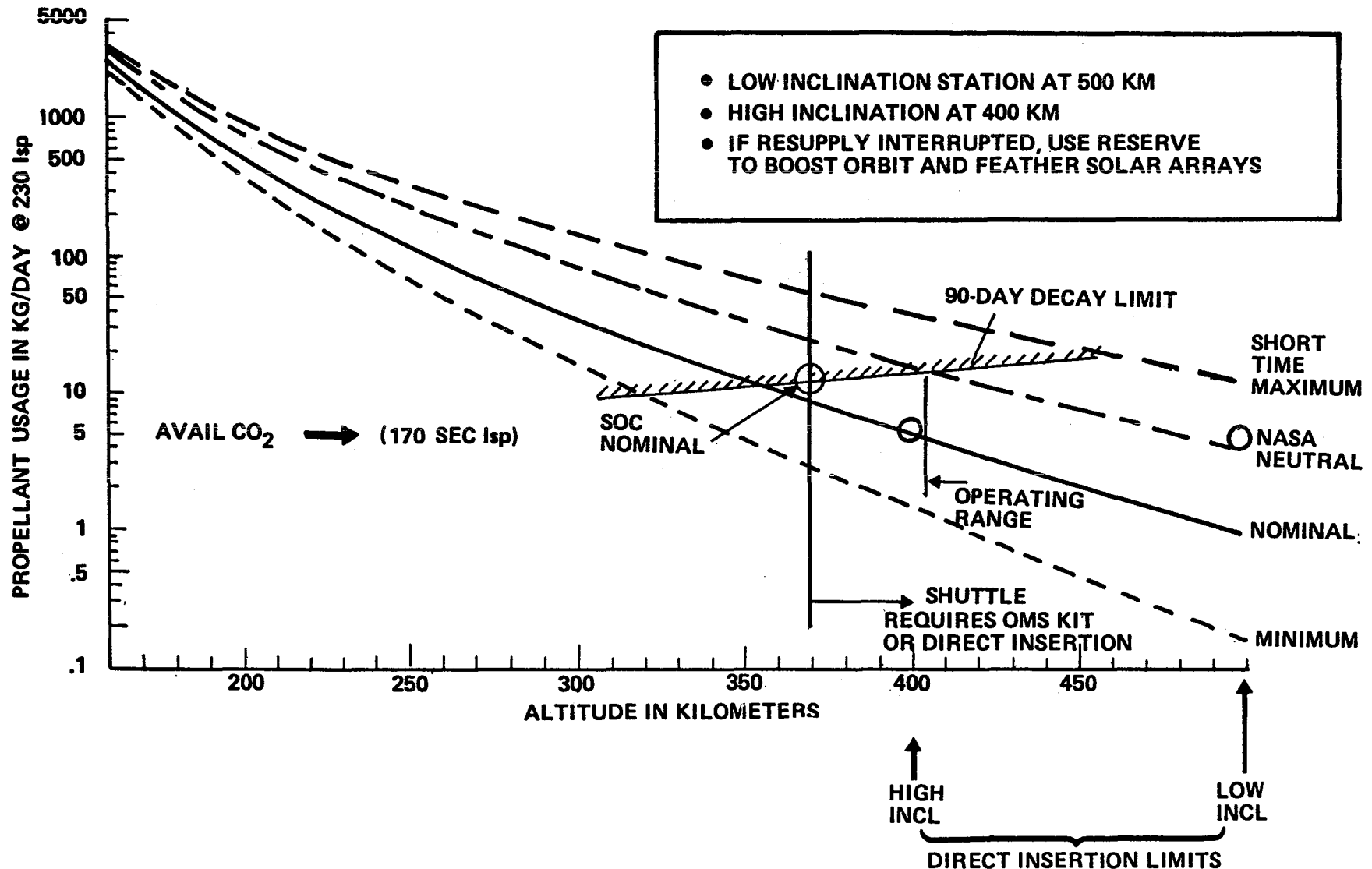
With direct injection we can expect to attain about 400 kilometers sun-synchronous and about 500 kilometers for low inclination orbits. This reduces the drag and orbit makeup propellant significantly.

The propellant usage as plotted is for mono-propellant hydrazine at an ISP of 230 seconds. Usage for other propellant combinations can be adjusted according to specific impulse. For example, the NASA neutral atmosphere at 500 kilometers would require approximately 4 kilograms per day of hydrazine or a little less than 2½ kilograms per day of water, using water electrolysis O_2H_2 gas propulsion, or about 5½ kilograms per day of CO_2 if the latter is electrically heated to develop a specific impulse of about 170 seconds.

The available CO_2 , if CO_2 is not recycled within the ECLSS system, is spotted on the chart at the level of the hydrazine equivalent. Thus, the available CO_2 would nearly always be sufficient to maintain the orbit in the low inclination case and about half the time sufficient in the high inclination case.

Propellant Usage vs. Altitude

8-Man Station at 50kW

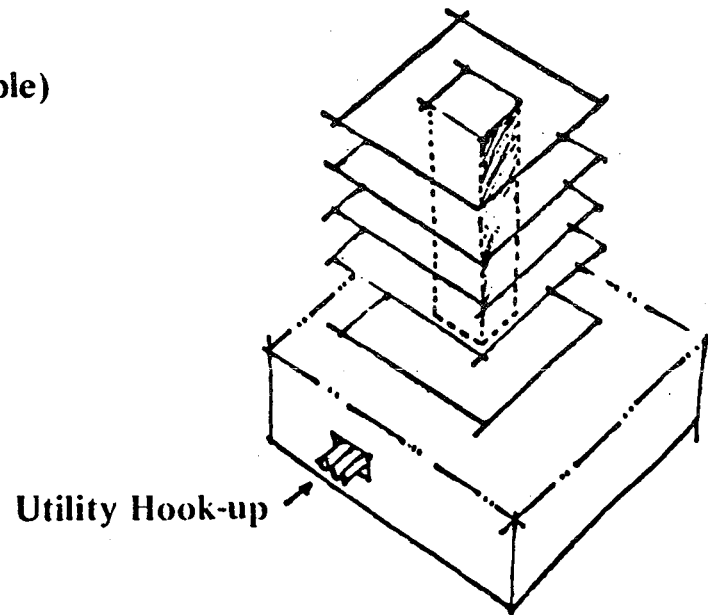


SPECULATIVE OFFICE BUILDING ARCHITECTURE

Early in the space station study we struck an analogy between speculative office building architectural development, as illustrated on the facing page, and space station architectural development, as illustrated on the following page. This analogy permitted us to begin space station architecture investigations long before mission requirements were clarified and quantified. The analogy points out that many influences on space station architecture arise from constraints and factors other than mission accommodation. These constraints were taken into account in beginning the architectural studies.

Speculative Office Building Architecture

- **Core functions**
 - Mechanical/electrical
 - HVAC
 - Hygiene
 - Structure
 - Phone
 - Circulation (people)
- **Planning**
 - Feasibility study
 - Pre-lease
 - Marketing



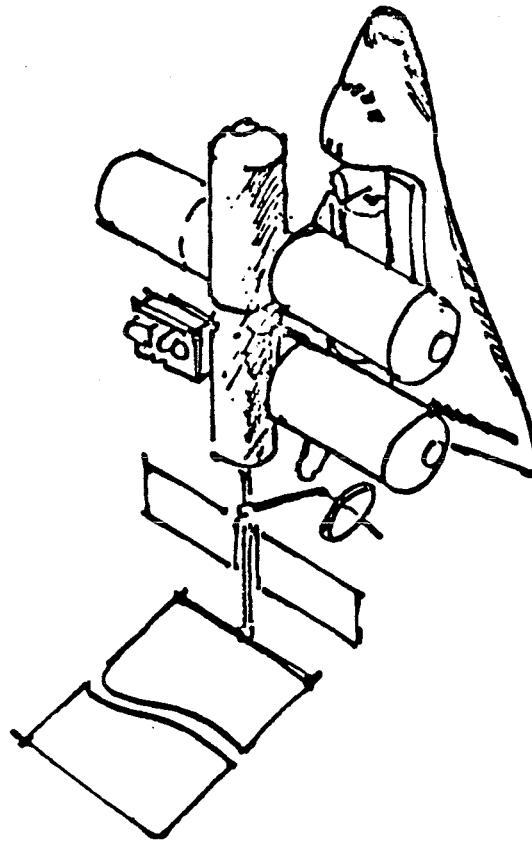
- **Architecture**
 - Physical boundaries (property lines)
 - Zoning
 - Height
 - Use
 - Setback
 - Fire zone
 - Safety code
 - Building code
 - Special use (handicapped)
 - Budget
 - Life cycle cost
 - Appeal (particular clientele)
 - Storage/parking
 - Economies of scale

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Space Station Architecture

- Core functions
 - Power and thermal control
 - ECLS
 - Hygiene
 - Structure (strong back)
 - Data link/comm.
 - Circulation (passageway)
- Planning
 - Feasibility study
 - Pre-lease
 - Marketing



- Architecture
 - Delivery envelope
 - Zoning
 - C.G.
 - Plume impingement
 - Array shadow
 - Fire regulations
 - Safety regulations
 - Construction specs
 - Military
 - Civil
 - Special use (EVA)
 - Budget
 - Life cycle cost
 - Application
 - Experiment
 - Operation
 - Storage/parking
 - Economies of scale

GENERIC SYSTEM ELEMENT LIST

We identified a list of generic space station elements expected to be present in almost any space station architecture. This list was derived from earlier studies and evaluation of available space station requirements data from the SOC studies. This list assisted us in developing the elements of space station architecture.

Generic System Element List

- Habitat Module
- Command & Control Module
- Service Module
- Laboratory Module
- Supporting Elements
 - Docking tunnel
 - Airlock module
- General purpose support equipment
 - Mobility/access systems
 - Handling equipment
 - EVA work station
 - Turntable/tilt table system
 - Umbilical system
 - Storage systems
- Construction support equipment
 - Cherry picker
 - Manipulator module
- Transportation support equipment
- Resupply and logistics support systems
 - Logistics module

WE STUDIED TWO CLASSES OF ARCHITECTURE

We divided the architectural options into open and limited classes. The open class accepted any technically feasible idea. It included such things as external-tank-derived space stations, tether concepts and large space stations launched on shuttle-derived launch vehicles.

The limited class was derived from a premise. The premise was succinctly stated by James Beggs last summer. It is printed on the facing page and indicates that the space station is permanent, manned, small at first, assembled and serviced by the space shuttle. This premise actually places many constraints on the space station, one of which, permanency, is illustrated along with the premise on the chart. The diagram illustrates how the attribute of permanency combined with orbit altitude limitations and solar array power requirements leads to the sizing of an orbit makeup propulsion system.

We Studied Two Classes of Architecture

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OPEN

LIMITED

● SHUTTLE EXTERNAL TANK

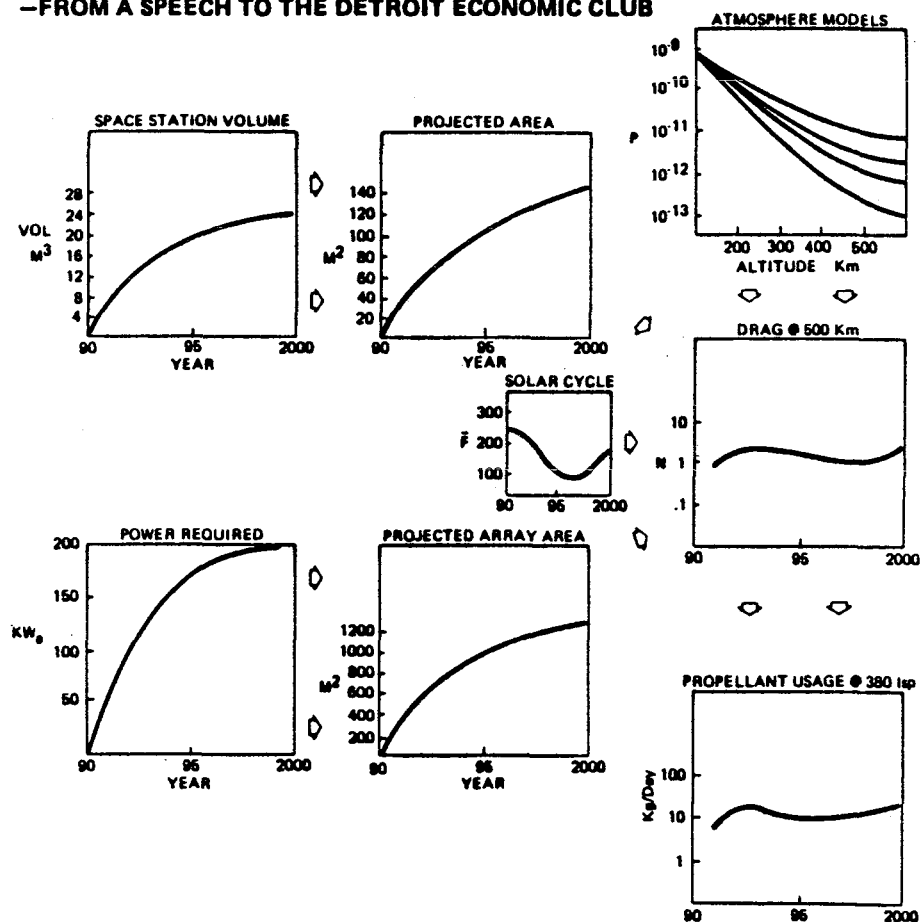
● TETHERS

● SHUTTLE DERIVED LAUNCH
VEHICLE

"I BELIEVE THAT OUR NEXT LOGICAL STEP IS TO ESTABLISH A PERMANENT MANNED PRESENCE IN LOW-EARTH ORBIT. THIS CAN BE DONE BY DEVELOPING A MANNED SPACE STATION. IT WOULD BE SMALL AT FIRST, ASSEMBLED IN ORBIT WITH MODULES CARRIED TO SPACE BY THE SHUTTLE.

JIM BEGGS, JUNE 23, 1982

—FROM A SPEECH TO THE DETROIT ECONOMIC CLUB



ARCHITECTURAL OPTIONS NOT RECOMMENDED

As we reviewed the open class options, we found problems that led to our decision not to recommend them for an early space station.

A heavy lift launch vehicle would permit orbiting a fairly capable space station on a single flight. However, such a system depends on availability of the launch vehicle, for which the timing is presently unclear. Further, such a large system could not be returned to the Earth by space shuttle in the event required for overhaul or major repairs.

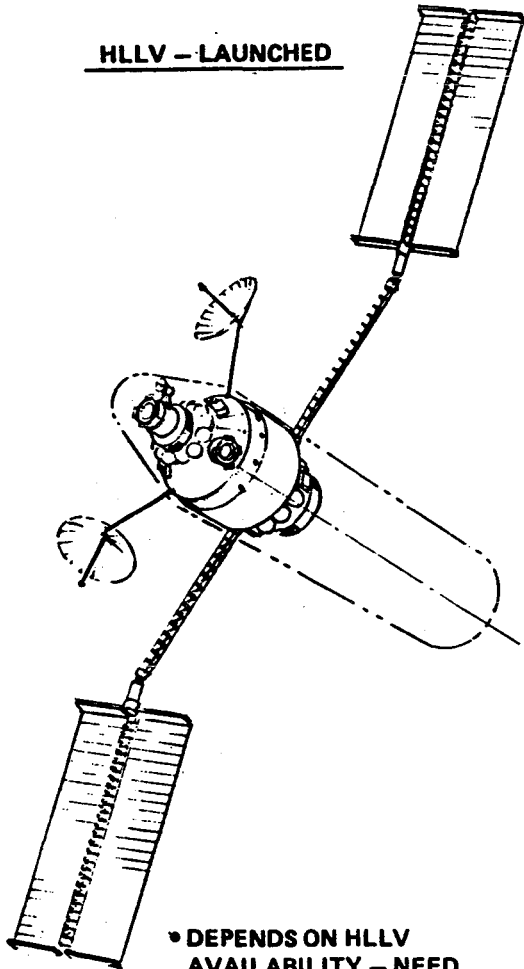
Similar objections were found regarding space stations based on external tanks. A modest space station can be designed into the aft cargo compartment space of the external tank, providing a relatively commodious habitat. However, we found no clear need or major advantages. Like the HLLV launched space station, it can't be returned to Earth. It tends to have less redundancy and backup capability in pressure volumes than modular designs. Finally, the external tank itself is a large object with large inertial differences. Such a system is difficult to fly inertially-oriented as needed for some of the scientific missions. We concluded that for the configuration depicted, approximately 20 Skylab CMG sets would be needed to maintain inertial orientation.

There is considerable interest in tethered concepts. Tethers offer some special capabilities not easily obtained in other ways. However, based on the mission requirements we identified, we found no major advantages for tethers. A tethered system adds flight control complexity (an issue already high on the priority list). Most of the tethered concepts would compromise the zero G environment necessary for materials processing and life sciences investigations. Tethers could provide an economical means of obtaining partial-G environments, important to some life sciences research. Tether systems need further study, but are not now recommended as a baseline architecture for an early space station.

Architectural Options Not Recommended

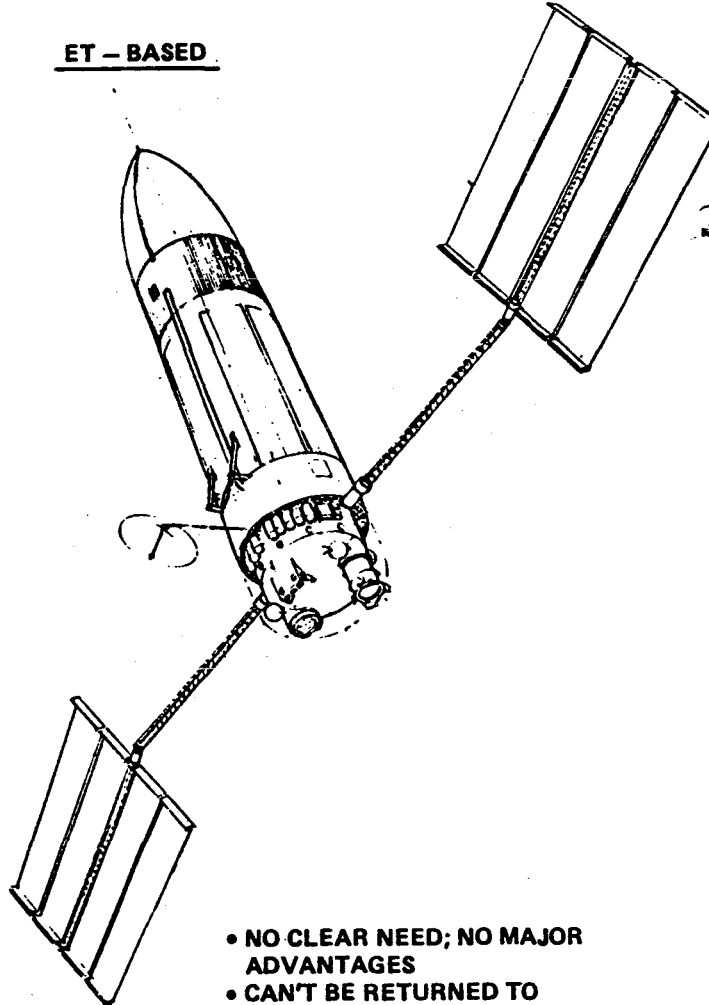
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HLLV - LAUNCHED



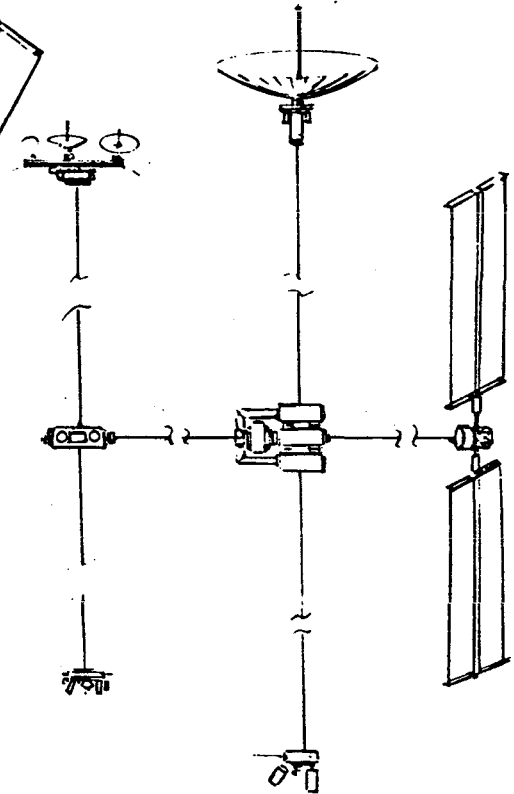
- DEPENDS ON HLLV AVAILABILITY - NEED FOR HLLV NOT CLEAR
- CAN'T BE RETURNED TO EARTH BY SHUTTLE

ET - BASED



- NO CLEAR NEED; NO MAJOR ADVANTAGES
- CAN'T BE RETURNED TO EARTH IN SHUTTLE
- LARGE INERTIAL DIFFERENCES - DIFFICULT TO POINT

TETHERS



- NO CLEAR NEED; NO MAJOR ADVANTAGES
- ADDS FLIGHT CONTROL COMPLEXITY
- COMPROMISES ZERO-G ENVIRONMENT

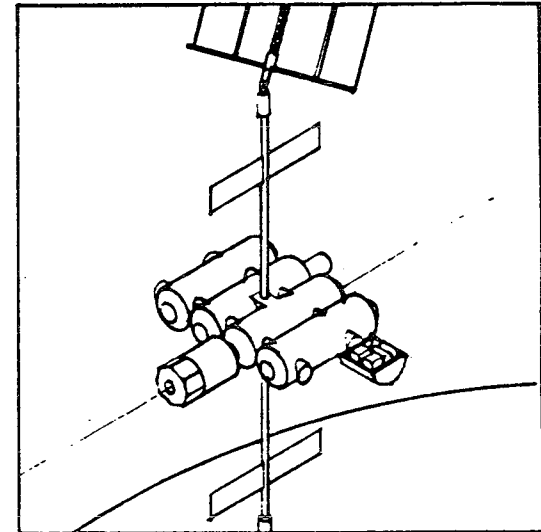
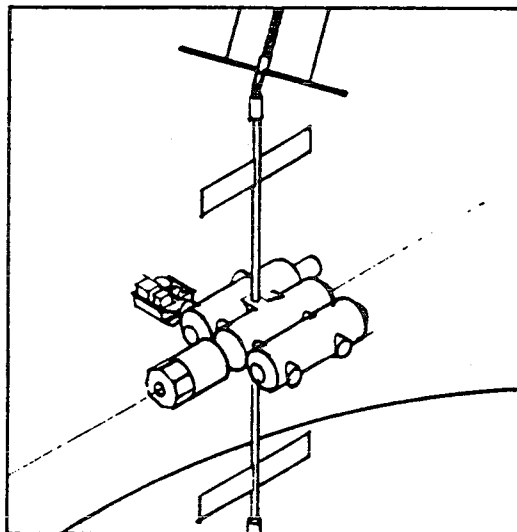
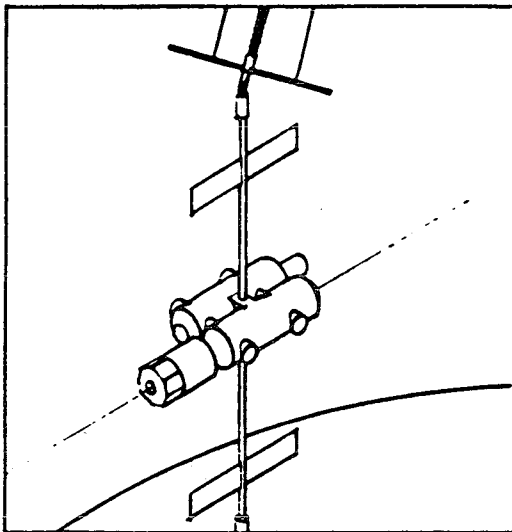
NEEDS MORE STUDY

MODES OF GROWTH

We began our study of the limited-class architectures by examining alternative means of growth. Growth approaches are important inasmuch as the early space station will probably accommodate four people, whereas the end-point system may need to accommodate as many as 15 to 20. Similarly, laboratory and other facility modules will be added, solar array power must be increased, and accommodations for mission payloads must increase.

We identified three generic means of growth, planar, branched, and three-dimensional. These three growth concepts and their pros and cons are summarized on the following three pages. The planar growth means was selected as preferable.

Planar Growth



PRO

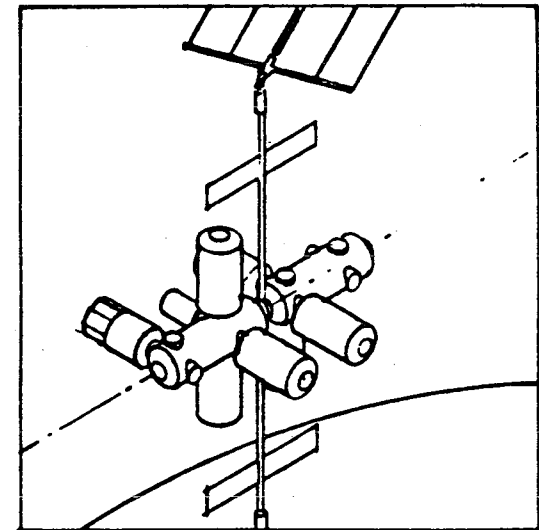
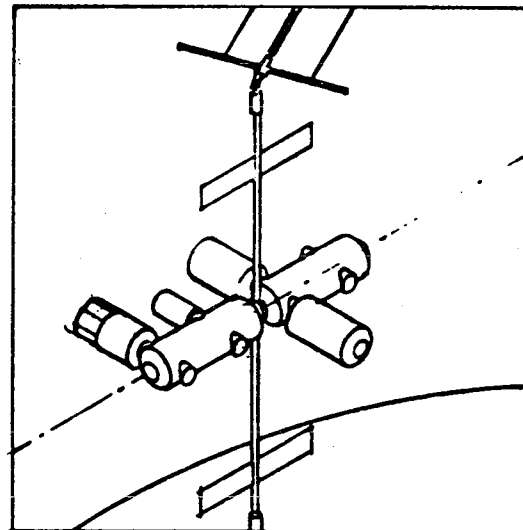
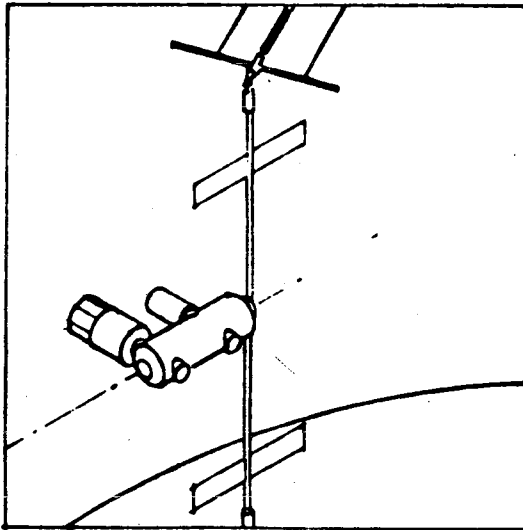
- AMPLE WORK SPACE FOR OPERATIONS
- TWO OR MORE EGRESS PATHS
- CAN BE ASSEMBLED BY SHUTTLE/RMS
- FAIR TO GOOD THERMAL VIEW FACTOR

CON

- INERTIAL DIFFERENCE OUTGROW CMG
- CAPABILITY FOR INERTIAL ORIENTATION
- EARTH ORIENTATION RESTRICTED TO STATION PLANE IN ORBIT PLANE
- LIMITED GROWTH

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Branched Growth



PRO

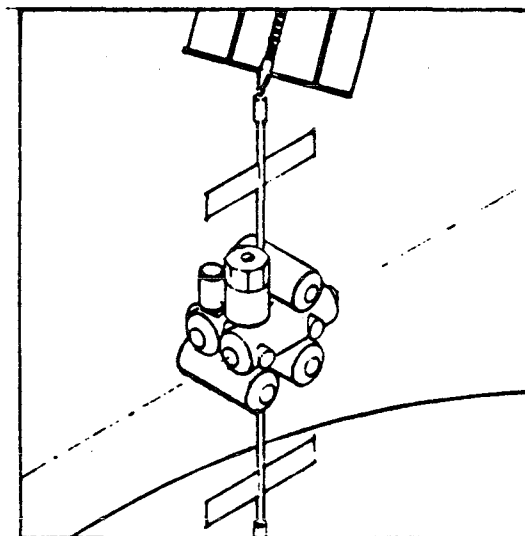
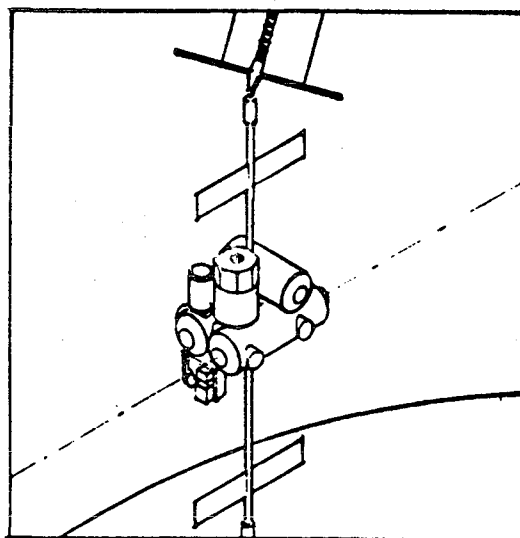
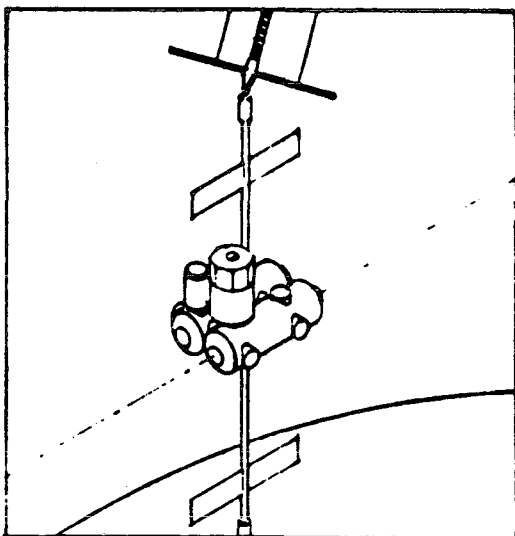
- CAN GROW INDEFINITELY
- MORE FLEXIBLE FOR INSTRUMENT POINTING AND ATTACHMENT
- FAIR TO GOOD THERMAL

CON

- OPERATIONS WORK SPACE CUT UP—MOBILITY DIFFICULT
- LACK OF DUAL EGRESS PATHS VIOLATES JSC SAFETY RULE
- TENDS TOWARD LARGE INERTIA DIFFERENCES

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3-Dimensional Growth



PRO

- TWO OR MORE EGRESS PATHS
- INERTIAL SYMMETRY PERMITS ALL ORIENTATIONS

CON

- OPS WORKSPACE RESTRICTED; MOBILITY DIFFICULT TO IMPOSSIBLE
- DIFFICULT TO ASSEMBLE, BUT RMS REACH OK
- POOR MODULE SURFACE THERMAL VIEW FACTORS
- GROWTH IS LIMITED

TYPICAL FOREIGN INPUTS

Our discussions with representatives of companies from other nations indicated potential foreign contributions to an international space station program as listed on the facing page. We attempted to make our architectural approaches compatible with such foreign contributions in the event the United States decides to undertake a program with international content.

Typical Foreign Inputs

Canada	—	Manipulator arm
ERNO	—	Lab modules Resupply?
BA/Telefunken	—	Solar array
Dornier	—	Instrument pointing system Thermal control Crew accommodations
Aeritalia	—	“Can” structures
Japan	—	Robotics Resupply? Lab module Free flyer platform

RECOMMENDED ARCHITECTURAL OPTIONS

We developed three recommended space station architectures. One is an incremental approach that provides a maximum of flexibility and adaptability for both high and low inclination orbits (and even high altitude orbits). The flexibility is provided through a number of different types of modules. The second approach was a unified approach that emphasized maximum commonality between modules, permitting more rapid growth for the low inclination space station, but sacrificing capability to operate in high inclination orbits because of the mass of its unitary module.

Finally, we developed a derivative free-flyer platform derived from manned space station architectural elements. The derivative version is not described in this summary briefing.

We developed considerable design detail. These were needed to support cost analyses as well as mass properties, inertia, and center of gravity compatibility with the space shuttle. These details were necessary to assess the viability of the basic design strategies. The significance of these architectural options is in the underlying design strategies and not in the details. The details represented point designs based largely on our prior experience from earlier and concurrent space station studies, on engineering judgement, and on technology considerations. The details were not supported by the full array of trade studies that would be necessary to finalize space station configurations at the level of detail depicted.

Recommended Architectural Options

- **We developed three recommended space station architectures.**
 - **Incremental, providing flexibility and adaptability for high and low inclinations.**
 - **Unified, providing maximum commonality between modules for more rapid growth, but sacrificing high inclination compatibility.**
 - **Derivative, a free-flyer platform derived from manned space station architecture.**
- **Design details were developed to support cost analyses and assess viability of the design strategies. The strategies are important, but the details are only illustrative.**

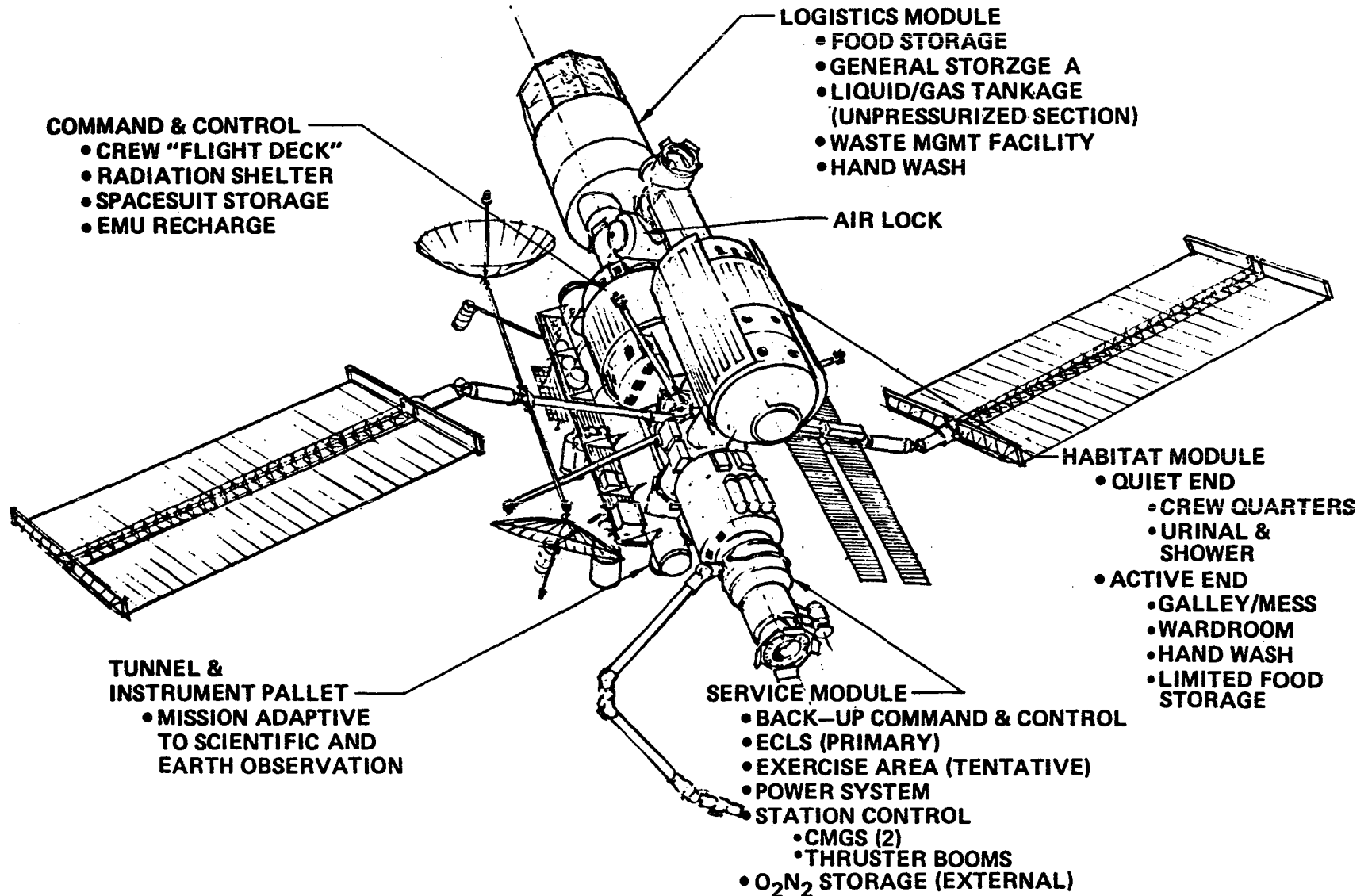
INCREMENTAL ARCHITECTURE

This figure illustrates the incremental architecture as arranged for high inclination operations. The service module would be launched on the initial flight. The next shuttle flight would deliver the command and control module. A third shuttle flight would deliver the logistics module and permit initial manning of the space station with a crew of two or three. A fourth flight would deliver the habitat module to permit increasing the crew size to four and allowing more generous crew accommodations. Mission payloads, tunnels, and airlocks would be delivered on additional flights. Depending on the weight of the logistics module, the airlock could probably be delivered on the logistics module flight.

These modules are sized to permit their launch singly to high inclination orbits and two at a time to low inclination orbits where the shuttle has a much greater lift capability.

Incremental Architecture

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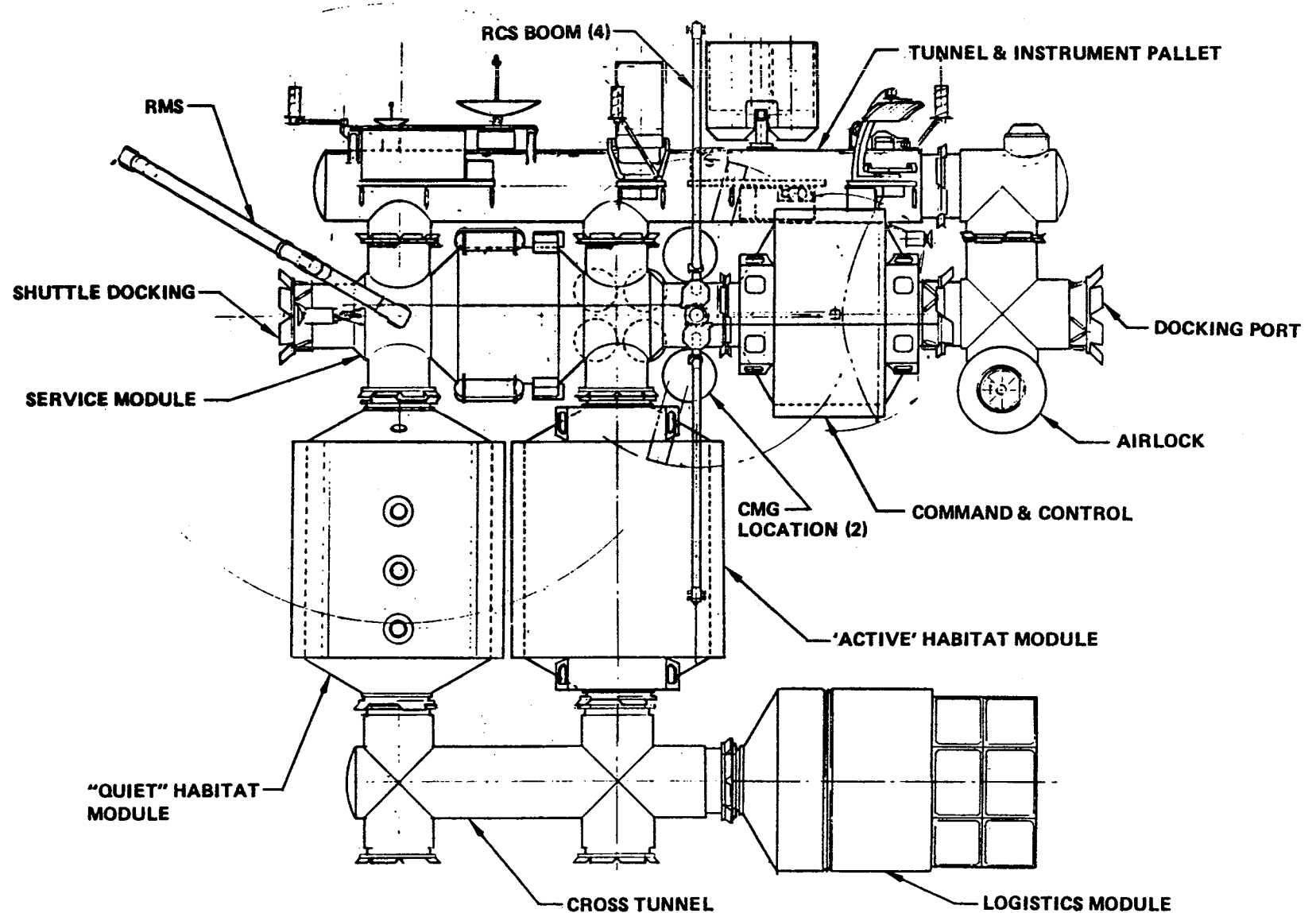


INCREMENTAL ARCHITECTURE—ORBITAL PLANE VIEW

This view shows a somewhat larger version of the incremental high-inclination station. This configuration might be used, for example, if national security applications in this orbit required additional crew members (beyond the four identified for science and applications missions).

Incremental Architecture

Orbital Plane View

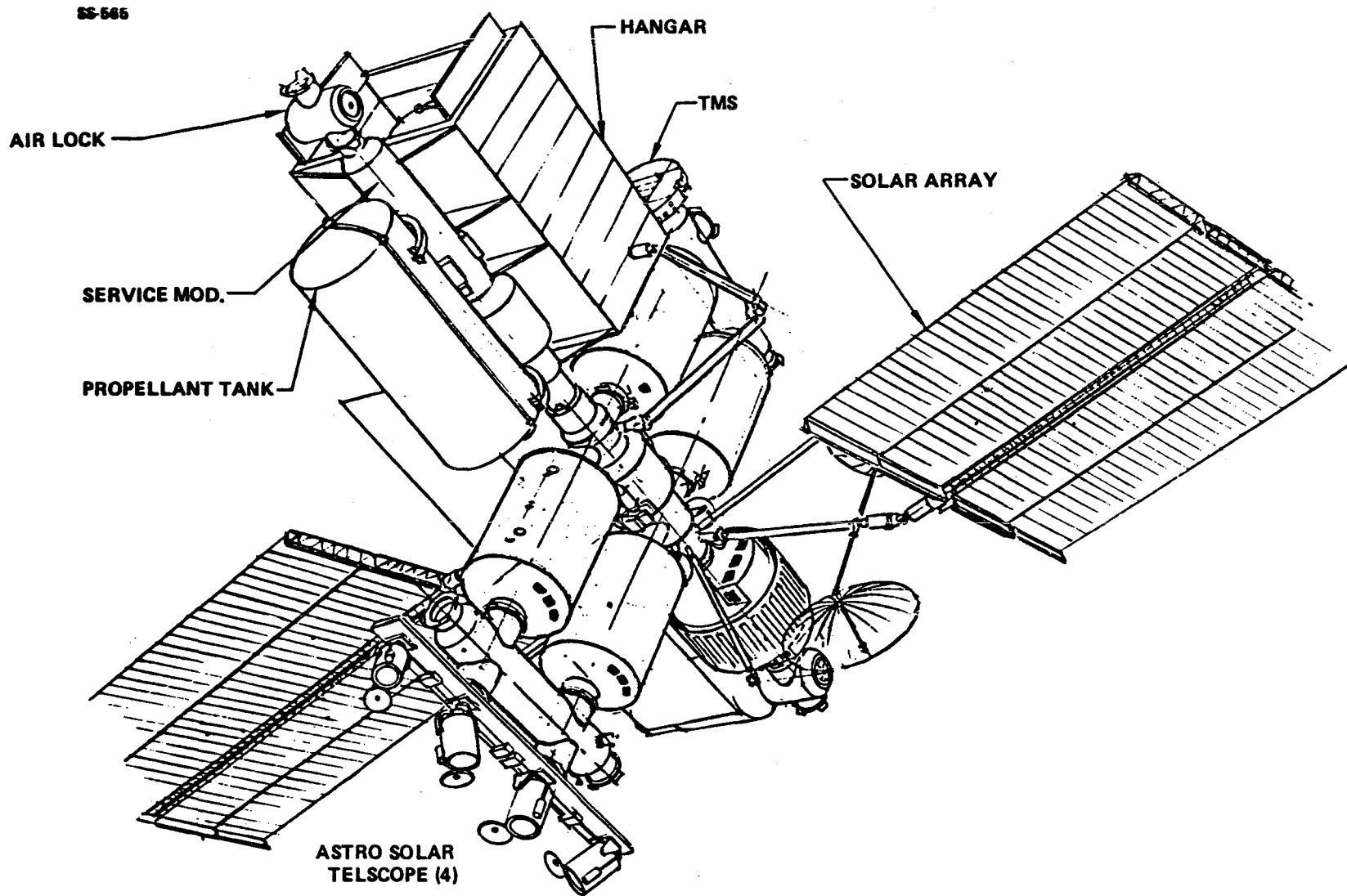


INCREMENTAL SPACE STATION EVOLUTION END-POINT (LOW INCLINATION)

The evolutionary end-point for the incremental architecture is sized to house a crew of 15 people, provide adequate laboratory space and provide servicing of upper stages as illustrated in this figure.

The evolutionary end-point depicted needs further analysis to assess compatibility with required construction operations, to assess its practicality from the standpoint of station assembly, shuttle docking clearance, inertias, and other operational factors. Based on our SOC experience which dealt with substantially larger modules, we do not believe that there are any fundamental problems with this architecture in these areas, but the necessary analytical procedures have not been carried out.

Incremental Space Station Evolution End Point (Low Inclination)



UNIFIED SPACE STATION - EARTH FACING VIEW

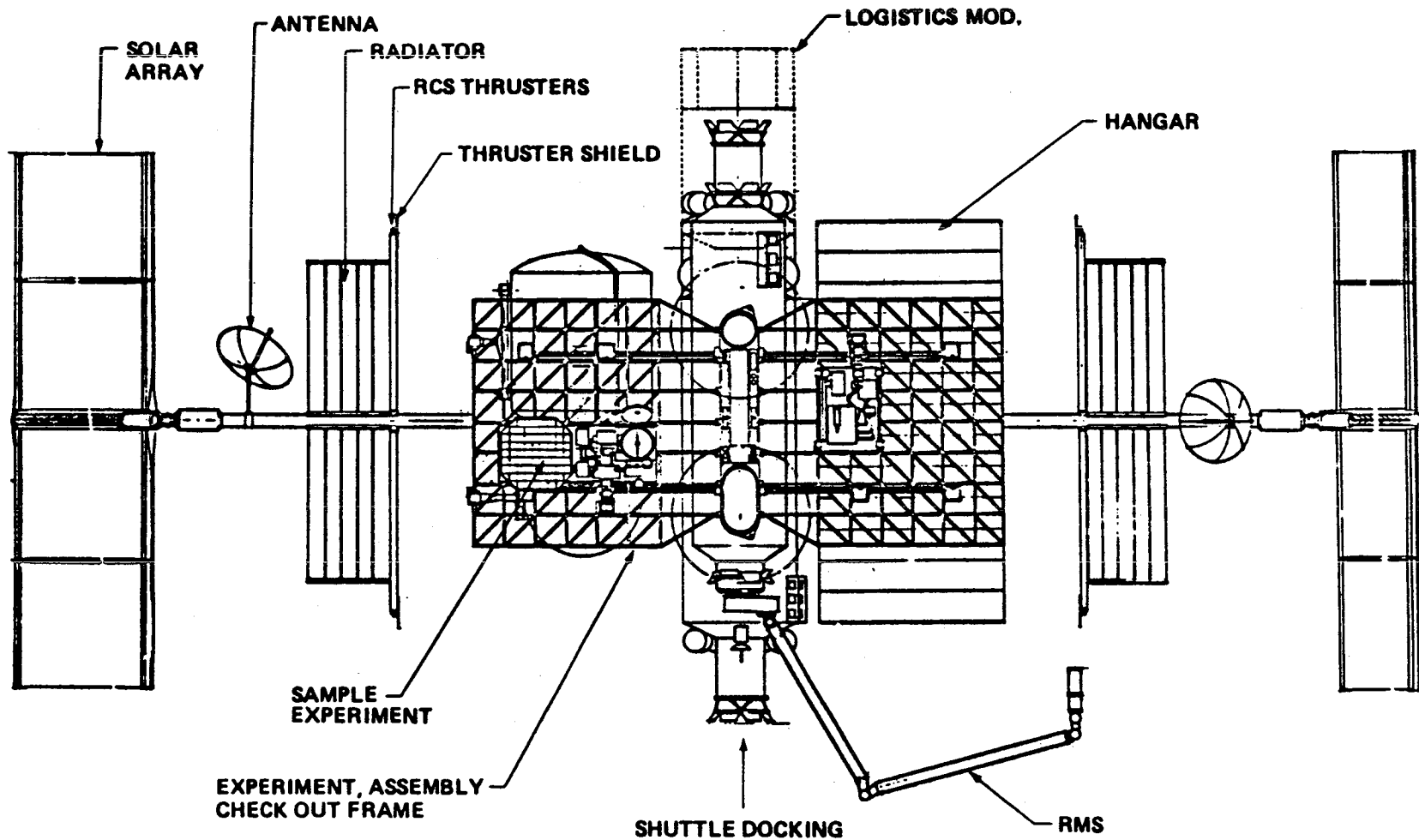
The unified space station relies on a single major module configuration to provide both habitat, work and laboratory space. The only other space station module required is a logistics module. Smaller articles include platforms for mounting mission equipment and upper stage servicing areas.

The unified module is too massive to be launched to the high inclination orbit.

Unified Space Station

Earth Facing View

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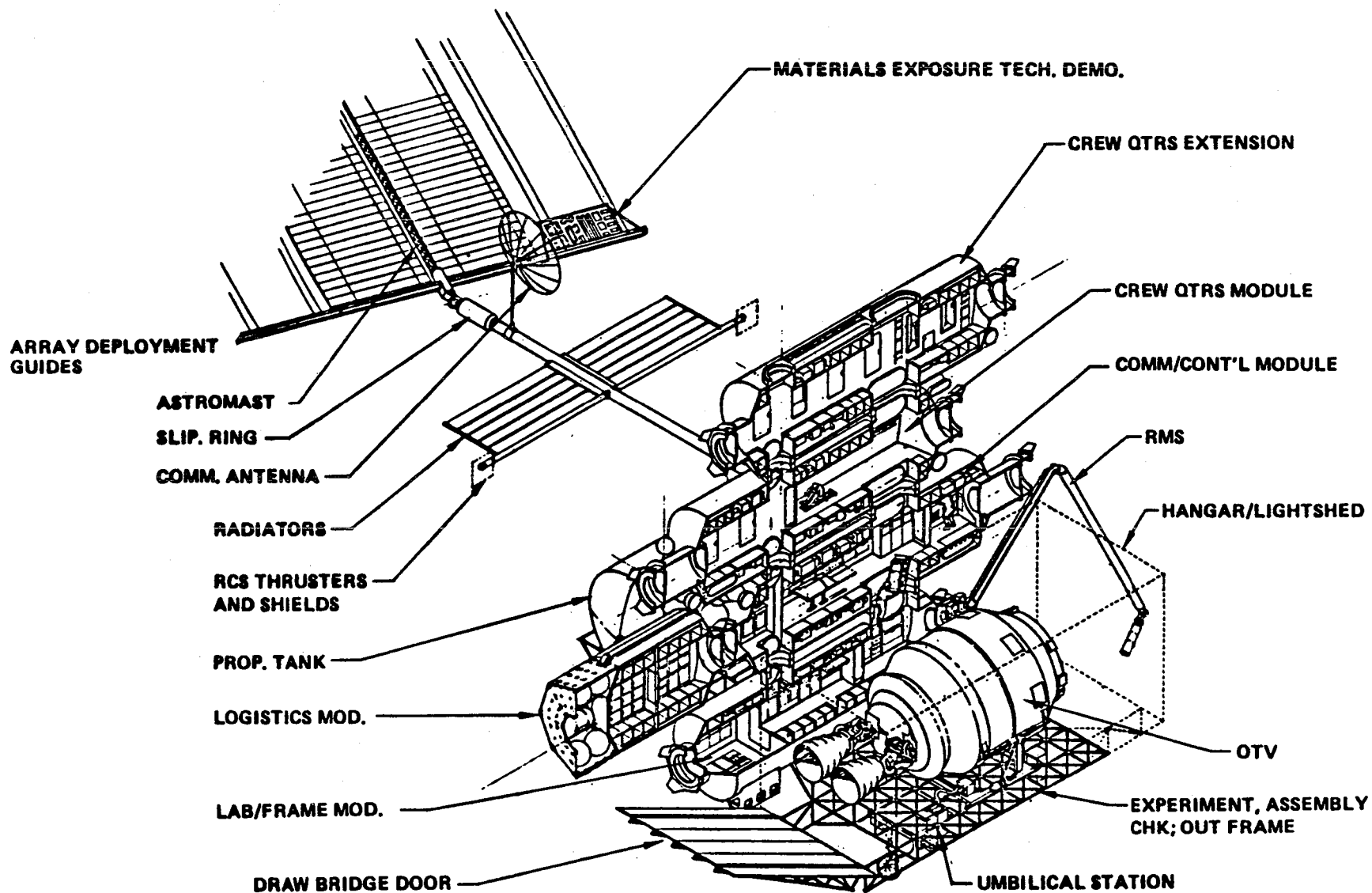


CUTAWAY VIEW OF UNIFIED SPACE STATION ARCHITECTURE

The comparatively large size of the unified architecture module permits a relatively capable space station to be built up from relatively few modules and shuttle flights.

Note the use of side-berthing to provide multiple egress paths and utility connections between modules.

Cutaway View of Unified Space Station Architecture



MASS PROPERTIES COMPARISON

Mass properties summaries are presented here for the incremental architectural service module and command module, and the unified architecture module. These summaries are based on detailed weight estimates to be provided as a part of the study documentation. Growth was allocated as 33% of identified weight excepting for the cabin shell and the mission equipment. The cabin shell was not included in the growth estimate because the wall thickness is sized for collision protection. The mission equipment was not included because it is relocatable.

Mass Properties Comparison

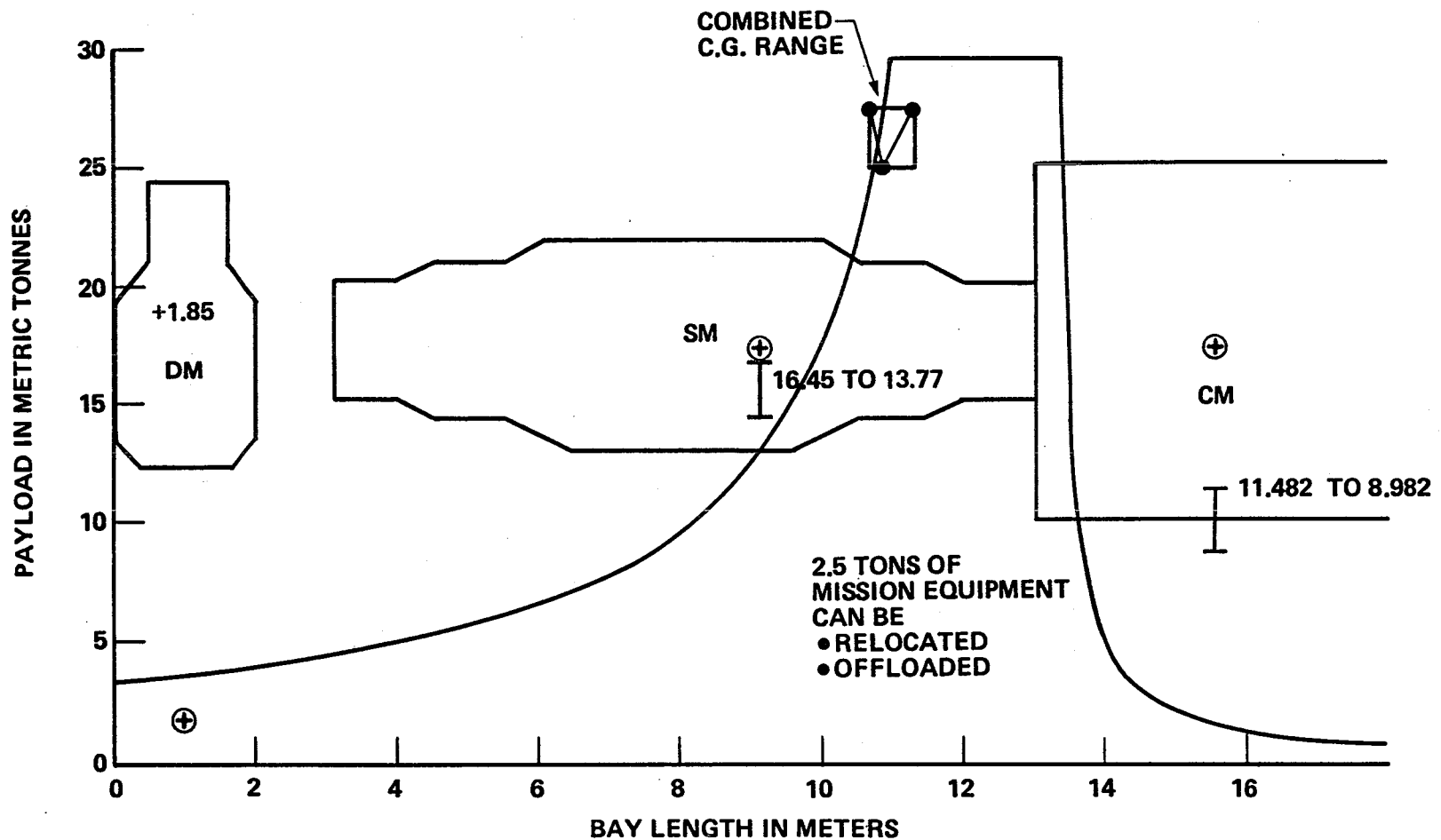
Item	Incremental Architecture				Unified Architecture	
	Service Module		Command Module		Standard Module	
	kg	lb	kg	lb	kg	lb
Structures	3562	7852	2981	6571	6798	14987
Cabin Shell	3104	6843	2142	4722	4236	9339
Other	458	1009	839	1849	2562	5648
Mechanisms	546	1203	164	361	408	899
Thermal Control	684	1507	831	1832	1364	3007
Auxiliary Prop	919	2026	0	0	587	1294
Ordnance	12	26	32	70	10	22
Electric Power	2609	5751	270	595	3478	7667
GN&C	720	1587	100	220	420	926
Tracking & Comm.	440	907	248	546	653	1440
Data Management	175	385	568	1252	481	1060
Instrumentation	100	220	36	79	100	220
Crew Accommodations	0	0	50	110	306	675
EC/LSS	829	1827	1475	3251	1911	4213
Mission Equipment	3026	6671	705	1554	1844	4065
Fixed	524	1155	73	160	100	220
Relocatable	2502	5516	632	1394	1744	3845
Growth	2690	5930	1522	3355	3854	8497
TOTAL	16312	35961	8982	19801	22214	48973

CENTER OF GRAVITY STRATEGY

The center of gravity limits of the shuttle payload bay for heavy payloads are quite narrow. The center of gravity envelope is illustrated on the facing page together with approximate lengths and shapes of the service module and command module for the incremental architecture. Also shown is a docking module that must be carried in the payload bay for the shuttle to dock or berth with a space station, providing a pressurized tunnel passageway between the shuttle cabin and a space station module. Mass of this docking module was estimated by Rockwell in the Space Operations Center studies as 4,000 lbs. or 1.85 metric tons.

The service module and command module weights are variable depending on location and disposition of mission equipment and the quantity of orbit makeup propellant loaded into the system for the initial launch. By shifting the relocatable mission equipment into the command module for launch the combined CG range can be brought within the shuttle CG envelope.

Center of Gravity Strategy



MASS AND CENTER OF GRAVITY STRATEGY

The strategy for observing shuttle mass and CG limits for the incremental and unified architectures for low inclination and high inclination are summarized on the facing page. Weights presented on this figure are in pounds in view of familiarity with shuttle performance capabilities in terms of pounds of transportation weight.

Mass and CG Strategy

OPTION	AS WEIGHED	LOW INCLINATION		HIGH INCLINATION	
		CHANGES	MASS	CHANGES	MASS
INCREMENTAL					
SERVICE MODULE	35,961 LB	MOVE 5,000 LB MISSION EQUIPMENT TO CM	30,961 LB	DELETE M.E. LAUNCH W/O DM	30,961 LB
COMMAND MODULE	19,801 LB		24,801	DELETE M.E. ADD RADIATION SHELTER	31,000 LB *
STD 7-METER MODULE	24,500 LB *	LAUNCH 2 - ALL M.E. IN AFT	49,000 LB	LAUNCH 1	24,500 LB
UNIFIED	48,973	LAUNCH WITH HEAVY END AFT	48,973	NOT APPLICABLE	

* ROUGH ESTIMATE. DETAILED MASS ESTIMATE NOT PREPARED

TECHNOLOGY

Our principal recommendations for high leverage technology advancement are presented on the facing page. Subsystems technology recommendations were developed utilizing a matrix procedure in which technology selection interrelationships and principal mission orbit altitude and growth considerations were considered. The complete matrix appears in our final reports.

One item on the facing page merits special mention. It has been popular in the past couple of years to consider incremental closing of the EC/LSS water and CO₂ loops. This is claimed to save money in early years when crews and hence resupply requirements may not be all that large. However, we recommend closing the water loop initially to minimize resupply requirements. This is very important for the high inclination missions where shuttle flights will be available infrequently and lift capability is small.

A second reason for this recommendation is that if the engineering and integration required to close these loops is deferred until some hardware is in space, one may discover integration problems very difficult to solve by retrofit techniques. Consequently, we suggest that such deferrals of basic developmental and integration engineering create high technical and cost risks for the program. This consideration outweighs the relatively modest savings that might be achieved by deferring water loop closure.

One need not, of course, operate in the fully closed mode until the equipment and water purity are flight proven.

Technology

High-Leverage Items

- Integrated O₂-H₂ (gas) system for electrical energy storage and propulsion.
- Data Management - Packet-switching redundant networks, fiber optics. Use the best available state-of-the-art.
- EC/LSS water loop closure to minimize resupply requirements important for high-inclination missions.
- Communications Bandwidth - Provide for growth to millimeter -wave and laser com.
 - Set the "requirement" at what the state of the art can deliver - Don't let it be a cost driver.
 - Be wary of specifying digital color TV. State of the art questionable. Potential cost driver.
- Long life thermal coatings and alleviation of thermal coating degradation problems through use of thermal storage and steerable radiators.
- Automated housekeeping subsystems - Integration of automated electrical, thermal and ECLSS subsystems using expert system techniques.

OTHER TECHNOLOGY ISSUES

There are further technology issues that merit discussion.

Our space station configurations utilize Astro-mast deployable solar arrays on booms to place the solar array away from the immediate space station operational area and to reduce solar array shadowing for Earth oriented station operation. This leads to structural modes with frequencies less than 1/10 Hertz, and has raised concern that precision pointing of instruments from such a soft structure may be difficult or impossible. The issue needs further assessment, but at present the goal appears within reach. Further study and assessment are needed before one accepts space station configuration compromises simply to increase stiffness.

We continued to assess external tank scavenging. It appears to be feasible as well as desirable for the era when the orbit transfer vehicle is space based. However, it is not attractive as an alternative to solar array power. Using scavenged propellants with fuel cells would result in severe resupply requirements during a time when it is important to minimize space station demands on space transportation. It should also be noted that earlier estimates of space station power requirements have been less than mission needs analyses indicated.

We believe that autonomy and automation, as well as standardization, have high leverages on initial and life-cycle cost for the reasons stated on the facing page.

Other Technology Issues

- **Stiffness and Flight Control**
 - This issue needs further assessment. Pointing goal appears within reach.
- **ET Scavenging**
 - Appears feasible and desirable for space-based cryo OTV
 - Not attractive as an alternative to solar array power
- **Autonomy and automation - High leverage on life cycle cost**

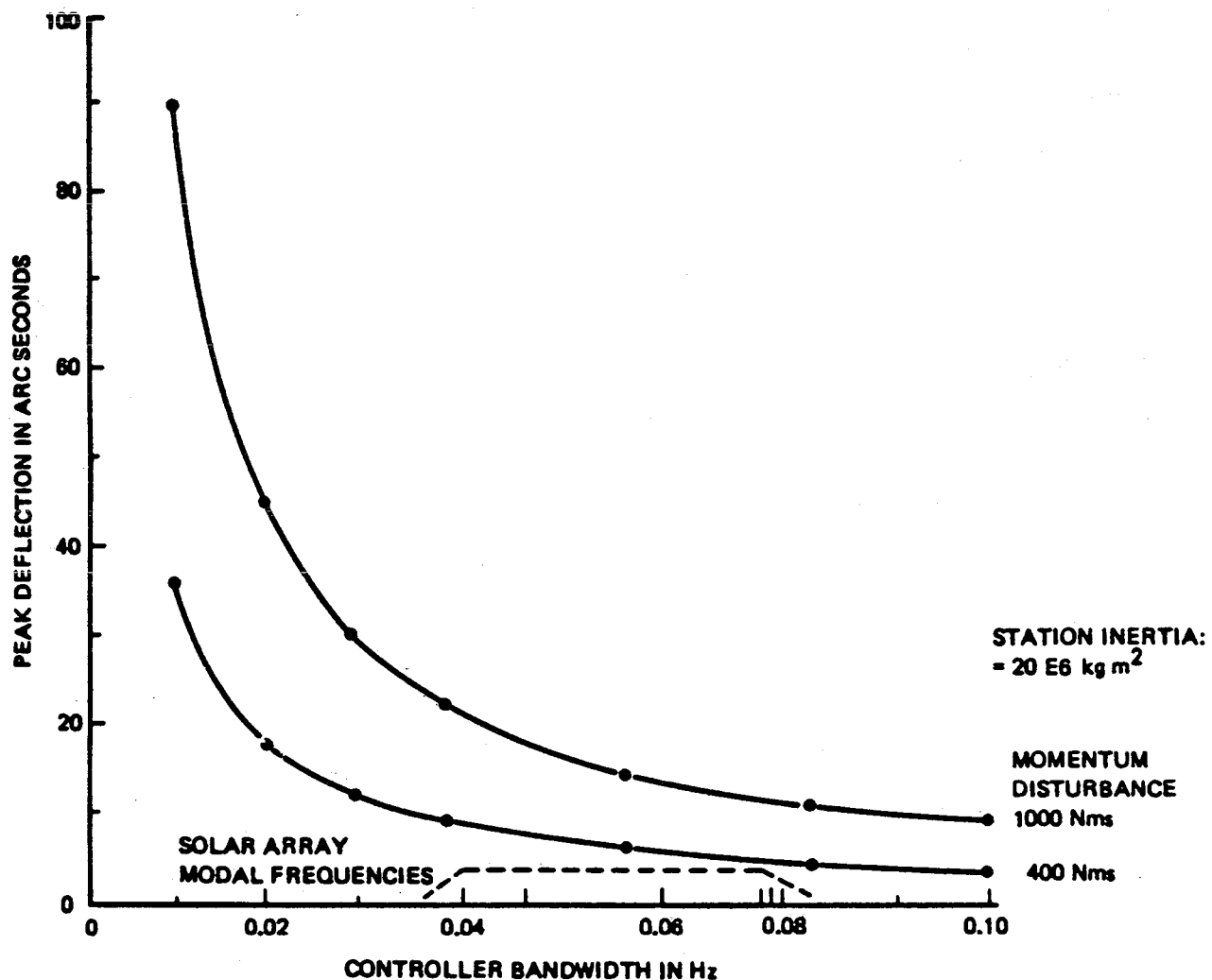
Automation should be used to reduce crew workload and eliminate dependence on large cadre of ground mission controllers. Put the flight crew in charge (like an airplane crew).
- **Standardization - High leverage on life cycle cost**
 - Use industry standard hardware and software wherever practical. Space qualify as necessary.
 - Unique/special designs require support of spares program over life of program.

SPACE STATION DEFLECTION AS A FUNCTION OF CONTROLLER BANDWIDTH

We conducted an initial evaluation of controller bandwidth requirements to achieve given attitude stabilities. Our nominal pointing stability goal is 5 arc seconds. We find that if the controller bandwidth is restricted to frequencies significantly below the solar array nodal frequencies determined for the SOC, the 5 arc seconds cannot be obtained unless one uses an instrument subplatform like the Dornier IPS to improve instrument pointing. Further analysis is needed to assess the degree to which solar array stiffness can be increased without making major configuration concept changes. Potential avenues include rigid panels instead of Astromast-deployed panels, and using stays and spreaders to increase mast stiffness.

Space Station Deflection as a Function of Controller Bandwidth

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CONTAMINATION STRATEGY

A frequently-stated mission need was for a low contamination environment. One approach is to locate contamination sensitive systems on a free-flyer platform. This, however, complicates servicing operations and requires EVA for servicing that might otherwise be done IVA.

We considered several measures to reduce space station contamination environments to a level acceptable for mission operations. Orbit makeup propulsion could be provided by resistojets using either hydrogen or EC/LS surpluses. At the 500-kilometer altitude for the low inclination station, orbit makeup maneuvers at higher thrust would be infrequent and could utilize the integrated hydrogen oxygen system we recommended.

Airlock outgassing is a source of contamination. Even though airlocks will be pumped down to conserve atmosphere, the minimum practical pressure will be 1/2 to 1 psi. When the airlock door is open, outgassing will issue from the airlock walls for a significant time. It is important to locate airlocks to eliminate direct paths from the airlock door to sensitive instruments.

Elimination of the water boiler from the EVA suit is important. The present shuttle toilet vents water vapor and other contaminants overboard. We need a no vent toilet.

Pressurized modules should be designed for low leakage. Historically, space station leakage specifications have been set at the resupply nuisance level, e.g. several kilograms per day. The leakage specification should be reduced to that consistent with good manufacturing and quality control.

The space operations center concept employed a principal-axis flight mode that was normally gravity stable together with attitude control thrusters to provide control authority when needed. The combination of need for low contamination and precision pointing leads to a requirement to provide control moment gyros on the station for normal attitude control operations, reserving the use of thrusters for situations when high control authority is needed.

Contamination Strategy

- Resistojets using H_2 and EC/LS surplus
- Location of airlocks
- Ice pack suit
- No vent toilet
- Low leakage design
- CMGs

COST DRIVERS SUMMARY

Our cost estimates for space station were derived assuming conventional space practices, i.e., we used a history-based parametric cost model without imposing any special assumptions. There is, however, evidence that significant cost savings might be achieved relative to our nominal estimates.

Our estimates assumed adequate definition; that is, we did not include cost penalties for excessive change activity. We also assumed that requirements that stressed the available state of the art would not be accepted.

Parametric cost models include environment or "platform" factors that slew the cost estimate. In the RCA PRICE model, "manned space" is the most costly environment of all. Other environments such as unmanned space or military aircraft are much less costly. This suggests that a careful review of specifications, standards and practices should be carried out to identify and eliminate those that are more costly than the benefit they provide.

Autonomy and maintainability will have such a large impact on life cycle cost that improper attention to either could negate space station economic benefits, which hinge on reasonable operational costs. Similarly, specification of a unique design where an industry standard could serve will have a severe impact on cost of maintaining a spares program. The issue is not new versus old technology, but how widely spares production and sustaining engineering costs are shared.

In certain instances where technology advancement is highly desirable, the space station program may become the vehicle for creating a new industry standard. This is believed true in the cases of (1) Data management network architecture; (2) integrated O₂-H₂ systems; (3) EC/LSS; (4) thermal control; and perhaps others.

Finally, we were exposed to one study that indicated thirty percent of the cost of a typical government program was in compilation of reports. The implication was that these were reports specified by contracts but not essential to accomplishment of the programs.

Cost Drivers Summary

ITEM	IMPACT ON				COMMENTS
	DDT&E	INVESTMENT	SPARE & SUPPORT	OPERATIONS	
INADEQUATE DEFINITION; EXCESSIVE REQTS	? BUT HIGH	? BUT HIGH	? BUT HIGH	? BUT HIGH	SOME COMPARISON STUDIES HAVE SUGGESTED FACTOR OF 2 BUT NO REAL BASIS TO COMPARE
SPECS AND STANDARDS	100%	100%	MODERATE	LOW	
AUTONOMY	LOW TO MODERATE	LOW	MODERATE FAVORABLE	VERY HIGH FAVORABLE	FAILURE TO IMPLEMENT COULD NEGATE SPACE STATION BENEFITS
UNIQUENESS VS INDUSTRY STANDARD	10%	10%	FACTOR OF 2 TO 5	?	ISSUE IS NOT NEW VS OLD TECHNOLOGY
PAPER	30%	30%	?	?	
MAINTAINABILITY	10%	10%	LOW	HIGH TO EXTREME	FAILURE TO IMPLEMENT COULD NEGATE SPACE STATION BENEFITS

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COST ASSUMPTIONS

The costing assumptions we used are summarized on the facing page.

Costing Assumptions

1984 dollars

No schedule problems

Good definition

Normal specs and standards

Industry standard where practical

Normal paperwork

25% spares

2½ sets support equipment

Support equipment complexity factor 1.5

SE&I and ground test complexity factor 2.0

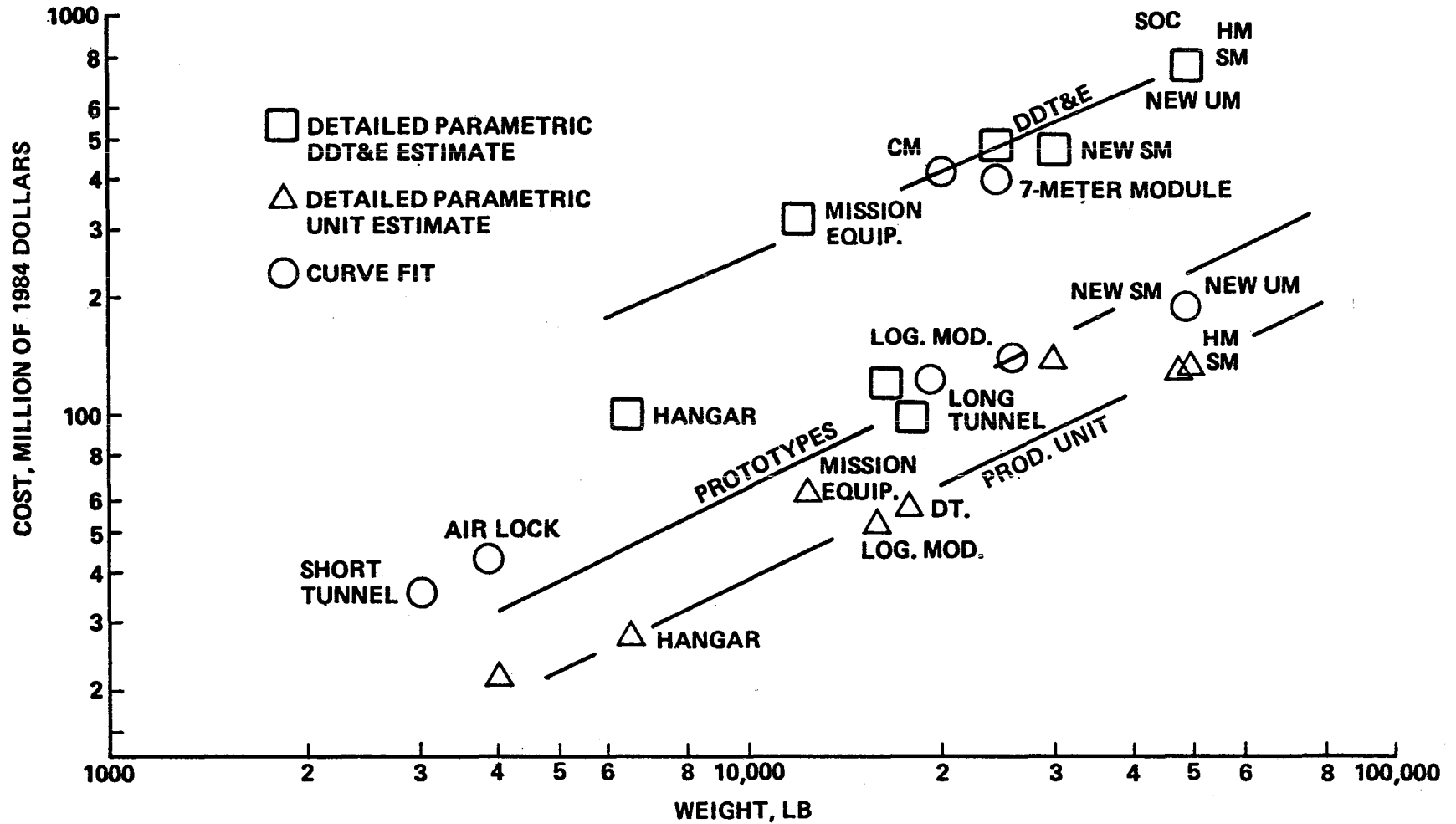
One prototype production unit used for integration testing

SYSTEM-LEVEL COST RELATIONSHIPS

We updated all of our space station cost estimating data base to 1984 dollars and plotted the results as shown. This permitted the use of high-level curve fits to estimate the costs of modules such as airlocks that were not estimated in detail. These data include modules defined by the SOC study, Boeing IR&D, and the present space station study.

Data are presented as defined in the parametric cost models, i.e., as DDT&E and unit costs.

System - Level Cost Relationships



COST ESTIMATES SUMMARY

Hardware acquisition and other costs are summarized on the facing page. In this tabulation, manufacturing costs associated with DDT&E have been transferred to the DDT&E column. A nominal contractor fee of 10% has been added (most cost models estimate cost, not price). These include a test unit for each module and nonrecurring manufacturing costs such as tooling.

Additional DDT&E charges are shown for subsequent unit acquisition, recognizing that these will not be identical to prior units. The additional charges were roughly estimated as 25% of the initial DDT&E.

A variety of "other" costs must be included in a complete program estimate. Some of these can be only roughly estimated at the present time. Those we have identified are listed on the right of the facing page.

Cost Estimates Summary

Values in Millions of 1984 Dollars

HARDWARE ACQUISITION (INCLUDES FEE)						OTHER COSTS
INCREMENTAL ARCHITECTURE			UNIFIED ARCHITECTURE			
ITEM	DDT&E*	INVEST.	ITEM	DDT&E	INVEST	
SERV. MOD.	725	165	UNIT MOD NO. 1	1250	220	SIL LAB(S) 60
C&C MODULE	670	130	UNIT MOD NO. N	315	220	PROGRAM-LEVEL 10%—20% INTEGRATION
AIR LOCK (2)	85	50	AIR LOCK (2)	85	50	FLIGHT SOFTWARE 100
7-METER NO. 1	710	165	LOGISTICS (2)	240	121	MISSION EQUIP
7-METER NO. N	180	165	HANGAR	165	35	SUITS, TOOLS, ETC ? SCIENCE, ETC. ?
SHORT TUNNEL	50	12	PROP STOR.	280	210	SUPPORT CONTRACTS ?
HANGAR	165	35	CONSTR EQUIP	350	165	TRAINING & SIMUL ?
PROP STOR.	280	210				SHUTTLE FLIGHTS 71
CONSTR EQUIP.	350	165				CIVIL SERVICE ?
						CONTINGENCIES 30%

*INCLUDES TEST HARDWARE & NONRECURRING MANUFACTURING

INITIAL COSTS OF ALTERNATIVE PROGRAM SCENARIOS

Initial costs of four architecture/program scenario options were estimated as summarized on the facing page. "Other" costs were included, as were considerations of numbers of hardware units required.

The "bare bones" program provides a permanent manned presence in space, but little else. The space station utilizes the incremental architecture without dedicated habitat or lab modules. It represents the minimum feasible space station program.

The program-constrained architecture paces space station buildup based on projected space station funding availability rather than onset of mission needs as projected by the mission needs analysis. The initial cost of this program is within the range of the NASA published estimates of four to six billion dollars.

The mission-driven program establishes stations in both low and high inclination orbits by 1992. It substantially exceeds the nominal NASA estimate.

Using the unified architecture and ignoring the high-inclination mission needs, a space station that serves the rapid onset of low-inclination missions can probably be acquired for less than six billion dollars.

If some of the cost saving potentials discussed on an earlier page could be realized, even the highest-cost mission-driven scenario could probably be afforded.

Initial Costs of Alternative Program Scenarios (1984 Dollars)

	INCREMENTAL ARCHITECTURE				UNIFIED ARCHITECTURE*
	BARE BONES PROGRAM (LOW INCL)	PROGRAM CONSTRAINED (LOW INCL)	MISSION DRIVEN		MISSION DRIVEN (LOW INCL)
			LOW INCL	HIGH INCL	
SERVICE MODULE	890	890	890	165	0
COMMAND MODULE	800	800	800	130	0
7-METER MODULES	0	1220	1220	345	2540 (3 UNITARY)
AIRLOCKS	135	135	135	100	135
TUNNEL	0	62	74	0	0
LOGISTICS MODULES	360	360	360	120	360
SIL LABS	60	60	60	20	50
FLIGHT SOFTWARE	50	100	100	50	100
LABS	0	0	690	0	0
MISSION EQUIPMENT	100	200	300	100	300
OTHER	100	200	200	100	200
SHUTTLE FLIGHTS	140	285	425	285	355
PROGRAM INTEGRATION	265	650	790	210	610
TOTAL	2900	4962	6044	1625	4650

*DOESN'T SUPPORT HIGH INCLINATION OPERATIONS

PROGRAM STRATEGY

The key points of our recommended program strategy are tabulated on the facing page.

Program Strategy

- **Examine high-inclination mission requirements, costs, and benefits and select architectural options for necessary flexibility.**
- **Structure program so that commercial and foreign users pay their own way as early as possible, i.e., investment phase.**
- **Select technologies compatible with potential DoD applications.**
- **Emphasize life cycle cost in all decisions.**
- **Zero-base requirements and specifications selection.**

CONCLUDING REMARKS

Our results indicate that a space station can provide scientific, economic, and social benefits. Further refinement of these results is needed, but we believe the need for permanent human presence in space is established.

The next year can be most profitably used by concentrating on how to achieve the program objectives at the lowest practical life cycle cost. This involves architectural, technology, and programmatic considerations.

Actualizing the space station benefits is critically dependent on control of life cycle costs.

Concluding Remarks

- **Role of man in space can be clarified, specified, and quantified.**
- **We have made a first detailed approximation.**
- **Space station benefits can be real.**
- **Practical, cost-effective architectures identified**
- **Definitive and comprehensive program planning required to actualize benefits.**

End of Document